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PRELIMINARY REPORT ON

FIRE HAZARD RATING STUDY

by

L. G. Gray,
Fire Weather Official,
U. S. Weather Bureau,
San Francisco, Calif.

March 15, 1933

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(Supplement to 1932 Annual Fire Weather Report,
California District)

By L. G. Gray,
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INTRODUCTION

Need for fire hazard rating

Definite and quantitative rating of fire hazard
may be said to be the ultimate aim and central prob-
lem of fire control and fire weather researches. In
view of present knowledge, scientifically precise
rating is but a remote future possibility, due to the
great number of complex and variable factors involved.
Practical approximations, more or less rough, are all
that can be expected at present. Both the forester
and the meteorologist increasingly find that definite
rating is essential to the most effective fire control
and to the forecasting and study of fire weather. To
the meteorologist, definite rating will permit of fore-
casts having more definite meaning in terms of expected
fire hazard, and will furnish a suitable scale for com-
parison in studies of fire weather. To the forester,
such rating will mean a more definite knowledge of past,
current and prospective fire hazard, which in turn will
promote more effective fire control in terms of any
accepted economic standard of forest protection.

Requirements of scale

It is essential, of course, that any rating scheme
finally adopted must agree with observed facts, and yet
deal practically with the broader rather than the great-
ly detailed aspects of the problem. It is desirable
that formulae be developed expressing all important re-
lationships, but tables and graphs in simplest form are
better adapted for field use, and should be employed
since they reduce the labor and skill required for cal-
culation and tend to minimize error. The units used in

the scale must be those most easily calculated and
measured, and must be of such nature as to permit
ultimate correlation with the primary factors in-
volved in measurement of fire control effort and
results, such as man power, funds, equipment and
damage. The factors considered in such a rating
scheme should be only those of fundamental or real
importance in the broad view of the problem. Greatly
detailed mathematical analysis is beyond present
possibility or would lead to relationships too in-
tricate for practical use.

Methods of attack on rating problem

There are essentially three methods of attack
on the fire hazard rating problem, although obvious-
ly all must be employed, either directly or as checks,
in securing final rating relationships.

1.) THEORETICAL METHOD-general physical law
applied mathematically and otherwise, supplemented
by hypotheses where current theory is lacking or
obviously inadequate.

2.) EXPERIMENTAL METHOD- laboratory or field
experimentation to determine facts, supplement theory
and verify hypotheses.

3.) EMPIRICAL METHOD-crudely, the application of
judgement gained by practical experience; more definitely,
solution by means of detailed statistical analysis of
records representing field experience.

Scope of this report

In view of the complexity of the problem, this re-
port must be considered merely as suggestive of possible
modes of attack and of the principal factors which ap-
parently must be considered in any satisfactory rating
scheme. The report indicates the progress made, using
the theoretical method. Much of the literature of com-
bustion and related subjects is obscure and faulty, and
a wide variation in values of physical constants used
appears. This report, therefore, attempts to collect and
consolidate for ready use some of the widely scattered
material directly pertinent to fire hazard rating study,
and to indicate suitable values for the various constants.
The data given have been checked by search through many

references and represent, so far as known, the best
values available for practical fire hazard rating
work. In some cases it has been necessary to attempt
to reconcile differences and adopt compromise values,
and in other cases, where authorities differed, the
value favored by the apparently "best" authority has
been used.

This report is limited to discussion of forest
fire hazard as distinct from other types of fire hazard.
It is a progress report, of preliminary nature, and
if some of the broad scale relationships are more defi-
nitely indicated than heretofore, its purpose will have
been accomplished.

PRINCIPAL GENERAL FACTORS AFFECTING FIRE HAZARD RATING

Fire hazard defined

The term "fire hazard", used in a general sense,
may be defined as the danger, risk, chance or probabil-
ity of fire.

The two aspects of general fire hazard

Fire hazard in general, as defined above, must be
considered from two aspects.

1.) INCEPTION HAZARD-the danger of fire start.

2.) TRANSLATION HAZARD-the danger of fire spread.

Elements necessary for combustion and fire hazard

The elements which simultaneously must be present
and operative so that fire is possible are

1.) FUEL SUPPLY-inflammable or combustible material.

2.) IGNITING AGENT-a source of heat sufficient to
cause ignition of fuel.

3.) OXYGEN SUPPLY-the element permitting and making
possible the chemical reactions involved in
combustion.

These three elements, together with a fourth, control
fire hazard.
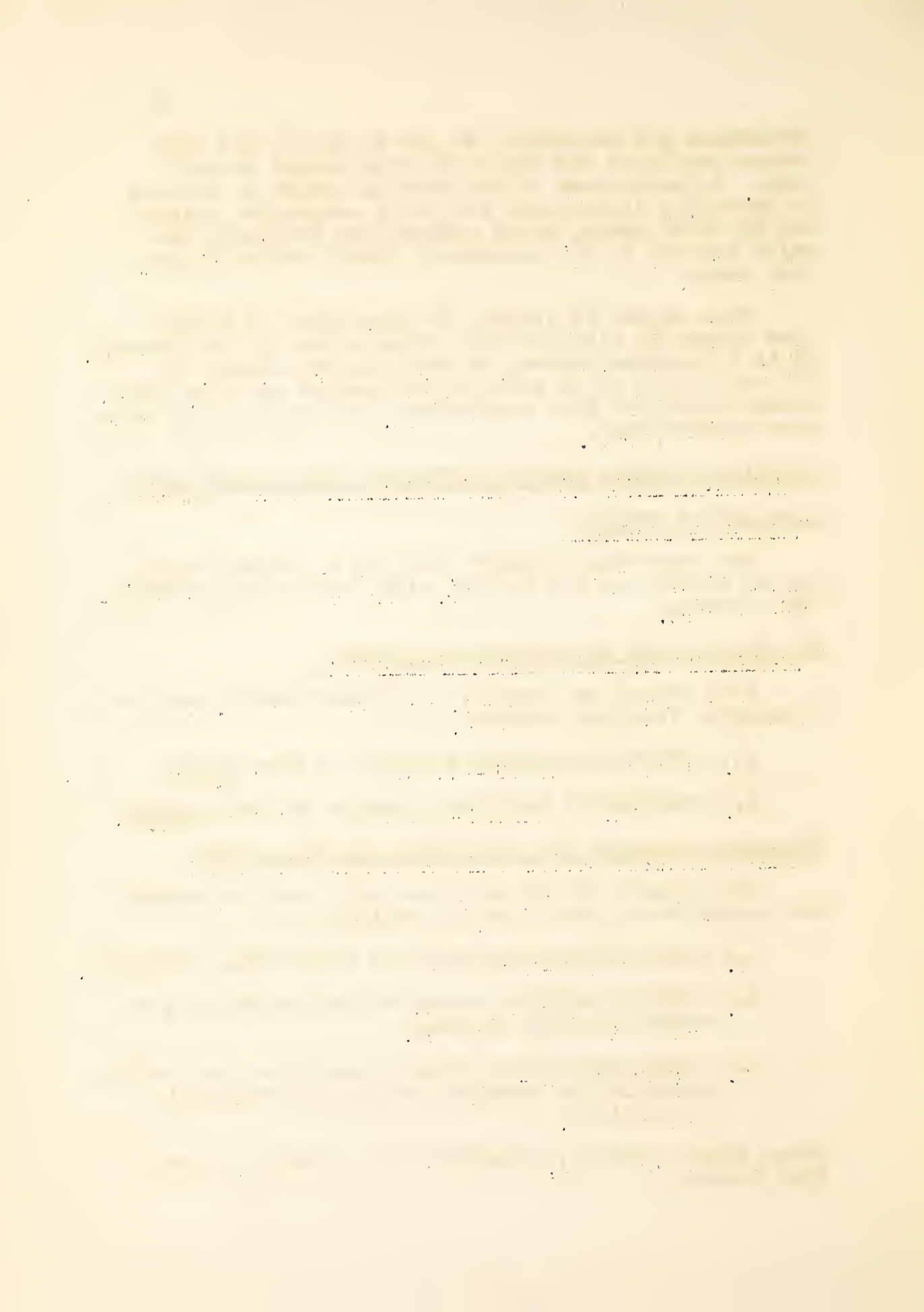
4.) MODIFYING INFLUENCES-numerous factors af-
fecting the foregoing three elements, es-
pecially in a quantitative sense.

PRINCIPAL DETAILED FACTORS AFFECTING FIRE HAZARD RATING

The following brief outline indicates in greater
detail those factors which must be considered in any
really satisfactory rating scheme. The outline may
not be complete, but it does indicate the principal and
obvious factors involved in fire hazard.

1. FUEL SUPPLY
   a. Species (general, as coniferous, deciduous, hard-
      wood, softwood; specific, as western yellow pine,
      California live oak, etc.).
   b. Type (light, as duff, grasses, ferns, mosses;
      heavy, as whole trees, snags, logs, stumps, etc.).
   c. Mensuration factors (quantity, size, shape, ratio
      of surface to mass and volume).
   d. Moisture factors (living or dead, fuel moisture
      content, state of moisture (solid, liquid, vapor)).
   e. Heat factors (heating value, specific heat, actual
      fuel temperature, ignition temperature).
   f. Disposition (detached, above ground, as tree crowns;
      compact ground layer, as duff; etc.).
   g. Physical structure and behavior.
   h. Chemical structure and behavior.

2. IGNITING AGENT
   a. Nature (type, size, shape, ratio of surface to mass
      and volume, disposition, physical structure and
      behavior, chemical structure and behavior).
   b. Moisture factors (moisture content, state of mois-
      ture).
   c. Heat factors (actual temperature, heating value,
      life, duration and rate of heat output, manner of
      application, atmospheric and other influences on
      effective heat).
   d. General factors (transport of sparks and embers,
      convection, conduction and radiation of heat).

3. OXYGEN SUPPLY
   a.Nature (from air and fuel).
   b.Amount (as affected by meteorological and physical
      conditions, including products of combustion and de-
      gree of effective contact with fuel).

4. MODIFYING INFLUENCES
  a. General (topographic, as slope shape, aspect
     and steepness; altitude, geographical location).
  b. Atmospheric factors (temperature, humidity,
     pressure, wind force and movement, cloudiness,
     precipitation, solar radiation, evaporation).
  c. Soil factors (nature of soil, temperature,
     moisture content and height of water table,
     evaporation losses of moisture, specific heat).
  d. Fire factors (size, shape, perimeter, amount
     of heat generated).
  e. Abstract factors (units used for measurement
     and calculation, standard conditions as ref-
     erence points, type of mathematical formula-
     tion employed, etc.).

DISCUSSION

General theory of combustion

Combustion or burning may be defined as a chemi-
cal union of constituents of a fuel with oxygen, ac-
companied by the evolution of heat. Usually the
term "combustion" is applied to the reaction when it
is violent and rapid. The term "oxidation" is used,
rather loosely, when the reaction is mild and slow,
relatively. In a sense, then, combustion is merely
rapid oxidation and oxidation is merely slow combus-
tion. The rate of the reaction largely determines
whether the phenomenon is combustion or oxidation,
as well as the amount of heat evolved in unit time.
The burning of wood, oil or coal is ordinarily rapid
and is representative of a combustion process. The
rusting of iron, the decay of wood, and the utiliza-
tion of food substances by the human body are types
of oxidations, in which the reactions are slower than
in active combustion, but result in the same products
as in ordinary combustion. The liberation of heat
by rusting iron or decaying wood is slow, and is not
readily perceptible. By the physical principle of
the conservation of heat (or energy), however, the
same total amount of heat is liberated regardless of
the speed of the reaction, whether combustion or oxi-
dation. If the reaction is slow, the evolved heat is
carried away by conduction, convection and radiation
as fast as liberated. If the reaction is rapid, heat
may be evolved faster than these processes can carry

it away, and hence the temperature rises appreciably.
If the material (such as hay or rags) is a poor heat
conductor, and there is sufficient air for oxidation
but not enough to remove the heat generated, heat
may accumulate and cause a temperature sufficiently
high to initiate active combustion. Such action is
termed "spontaneous" combustion.

Products of combustion

The products of combustion (or oxidation) are
chemical substances resulting from the union of fuel
constituents with the oxygen of the air, plus heat.
For wood fuels (which contain practically no sulphur),
the products of complete combustion are H_2O (water
vapor), CO_2 (carbon dioxide gas)and N_2 (nitrogen gas).
If combustion is incomplete by reason of insufficient
oxygen to combine with all of the carbon of the fuel,
the products are H_2O, N_2 and CO (carbon monoxide gas),
the latter instead of or in addition to a smaller amount
of CO_2. Quantitatively, the products of combustion
are as follows:

TABLE 1
Products of Combustion

Combustible Chemical Elements	Amt. Oxygen (lbs.) required for each lb. of combustible	Products*	Lbs. products per lb. of combustible
H (Hydrogen)	7.94	a:H_2O & 51658 Btu# heat b:H_2O & 6505 Btu# heat c:H_2O & 5778 Btu# heat d:H_2O & 61093 Btu# heat e:H_2O & 7694 Btu# heat f:H_2O & 6833 Btu# heat	8.94
C (Carbon)	2.67 (Complete Combustion)	a:CO_2 & 14352 Btu# heat b:CO_2 & 5309 Btu# heat c:CO_2 & 3861 Btu# heat	3.67
C (Carbon)	1.33 (Incomplete Combustion)	a:CO & 3963 Btu# heat b:CO & 2973 Btu# heat c:CO & 1699 Btu# heat	2.33

References, Table 1:
*Quantities of heat developed in reaction indicated differently, as follows:
 a: Gaseous product; heat per lb. of combustible.
 b: Gaseous product, heat per lb. of oxygen.
 c: Gaseous product, heat per lb. of product.
 d: Liquid product; heat per lb. of combustible.
 e: Liquid product, heat per lb. of oxygen.
 f: Liquid product, heat per lb. of product.

#Btu: British thermal unit; the amount of heat required to raise the temperature of one pound of pure water through one degree Fahrenheit, defined at 60 F.

The values given in table 1 were converted to English units from data given in the International Critical Tables (1). These heats of formation are for 64.4 F.

The chemical equations representing the reactions involved are as follows:

$$2H_2 + O_2 \longrightarrow 2H_2O + 103315 \text{ Btu (for 2 lbs. H)}$$
$$C + O_2 \longrightarrow CO_2 + 14352 \text{ Btu (for 1 lb. C)}$$
$$2CO_2 + O_2 \longrightarrow 2CO + 7925 \text{ Btu (for 2 lbs. C)}$$
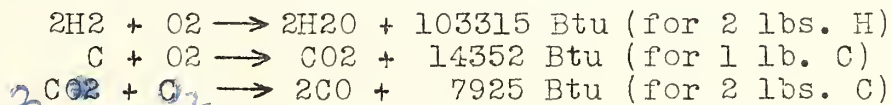
Nitrogen in fuels is considered to be evolved as a gas uncombined with any other chemical element during the process of combustion, and without the evolution of any heat. The incombustible mineral constituents of the fuel are unaffected and remain behind as a solid residue (ash).

The atomic weights used for calculation of Table 1 data are as follows:

O (oxygen).......16.0000
H (hydrogen)..... 1.0077
C (carbon).......12.0050

The process of combustion or oxidation is an extremely interesting example of energy transformation. Thus, plants take CO2 from the air, H2O from the soil, and N2 from the soil and by means of solar energy (heat) manufacture plant substances of complex CHNO (carbon, hydrogen, nitrogen and oxygen) composition. Combustion reverses this process by evolving CO2, H2O, N2 and heat from plant substances.

Fuel composition

The fuels involved in forest, brush, grass and grain fires are the various woods and woody substances, or fibers consisting principally of cellulose $(C_6H_{10}O_5)x$. Wood may be said, in general, to consist of cellulose plus a number of complex infiltrating substances collectively termed "lignin". It has been found that the general chemical composition of woods of various species is approximately the same, averages for woods common to the United States being as follows:

TABLE 2
Average Chemical Composition of Dry Wood (2)

Element	% by weight
Carbon (C)........................	49.70
Hydrogen (H)......................	6.06
Oxygen (O)........................	41.30
Nitrogen (N)......................	1.05
Ash (incombustible mineral matter, composition not specified).......	1.89
	100.00

The foregoing table is only approximately correct, because the content of resinous materials (saps, gums, resins, oils, etc.) of various woods differs in the relative proportions of each of many complex carbon compounds. The table, however, agrees closely with the composition of various woods, when reduced to chemical elements, without considering in what compounds these elements occur.

Density of wood substance

Since the composition of various woods is much the same, at least for the practical purpose of rating fire hazard, it follows that the density or specific gravity of wood substance itself, as well as its specific heat and heating value, should also be much the same for different species. Determinations made at the Forest Products Laboratory of the Forest Service at Madison, Wisc., on seven species of wood including both hardwoods and conifers, showed a range of only about $4\frac{1}{2}\%$ in the density of wood substance, or material of which the cell walls are composed. Since the density is so nearly constant, it may be said that

the density of a given piece of <u>dry</u> wood (including
wood <u>substance</u> and vacant cell spaces) is a measure
of the amount of actual wood substance contained in
it (3). Hawley and Wise (4) quote values for the
density of wood substance (determinations made by
Dunlap) ranging from 1.50 to 1.57, but state that
these results probably are too high, and that the value
of 1.475 (by Stamm) is nearer the truth, but still
slightly too high. A value of 1.47 is adopted for
this report.

Density of wood

The density of <u>wood</u>, as distinct from wood <u>substance</u>, refers to the weight of the wood sample oven
<u>dry</u> divided by the weight of an equivalent volume of
water. If the oven dry weight and the oven dry volume are used in determining the density, the <u>oven
dry</u> density results. Green and air dry densities may
also be used. However, for fire hazard rating purposes,
it is preferable to use oven dry densities determined
from the relation

$$\frac{wt. \ wood \ oven \ dry}{wt. \ H2O \ in \ oven \ dry \ volume}$$

rather than the air dry or green densities, since the
shrinkage and swelling wood undergoes with changes in
moisture content would complicate calculations unnecessarily. The following table gives values for oven
dry densities, taken from the International Critical
Tables (1), to which reference should be made for woods
not listed.

TABLE 3

Oven Dry Densities of Common Woods

Wood	Origin	Density
ALDER, red	Wash	0.434
ASH, Oregon	Ore	0.575
CASCARA	Ore	0.548
CEDAR, Alaska	Ore	0.439
CEDAR, incense	Ore.-Cal	0.365
CEDAR, Port Orford	Ore	0.440
CEDAR, western red	Mont.-Wash	0.344
CHINQUAPIN, golden	Ore	0.483
COTTONWOOD, black	Wash	0.368
DOGWOOD, Pacific	Ore	0.701

TABLE 3 (continued)

Wood	Origin	Density
ELDERBERRY, blue	Ore	0.570
FIR, Douglas, coast	Wash.-Ore.-Cal	0.512
FIR, Douglas, mountain	Wyo.-Mont	0.446
FIR, lowland white	Mont.-Ore	0.419
FIR, Noble	Ore	0.403
FIR, red	Cal	0.421
FIR, silver	Wash	0.415
FIR, white	Cal.-N.Mex	0.397
GUM, blue	Cal	0.796
HEMLOCK, mountain	Mont	0.480
HEMLOCK, western	Wash.-Ore	0.432
JUNIPER, alligator	Ariz	0.545
LARCH, western	Mont.-Wash	0.587
MADRONA	Ore.-Cal	0.694
MAPLE, bigleaf	Wash	0.513
MYRTLE, Oregon	Ore	0.589
OAK, California black	Ore.-Cal	0.578
OAK, Canyon live	Cal	0.838
OAK, Gambel	Ariz	0.701
OAK, Oregon white	Ore	0.748
PINE, Jeffrey	Cal	0.425
PINE, lodgepole	Wyo.-Mont.-Colo	0.434
PINE, sugar	Cal	0.378
PINE, western white	Mont.-Idaho	0.418
PINE, western yellow	Wash.-Cal.-Colo.-Mont.	0.420
PINON	Ariz	0.567
REDWOOD, gigantea	Cal	0.290
REDWOOD, sempervirens	Cal	0.436
SPRUCE, Sitka	Wash.-Ore	0.397
WILLOW, western black	Ore	0.473
YEW, Pacific	Wash	0.673

The need for data relating to wood densities in fire hazard rating will be apparent later. For the most accurate rating, it would be desirable to have density determinations at intervals, since the values given above are merely averages, and woods of the same species in groves only a short distance apart might easily have materially different densities. It also will eventually be necessary to have values for the foliage of various species, for grasses, ferns, tree mosses, bark and other light fuels.

Heating value of woods

While the composition of wood substance is fairly constant for practically all species, there is con-

siderable variation in the amount of resinous material
present in the cell spaces, as also in the nature of
the resinous material. The approximate specific grav-
ity of the resinous material is roughly 0.88, and its
heating value per pound is about 17400 Btu according
to Hawley and Wise (4). It is possible to calculate
approximately the heating value of various fuels from
the percentage composition, by Dulong's formula, but
the best results are those obtained by careful calor-
imeter measurements, since the resinous materials can-
not be entirely satisfactorily evaluated by formula.
Dulong's formula appears in several forms in different
"standard" textbooks on combustion, a common form being

$$HV = 14500\ C\% + 62100\ (H\% - \frac{O\%}{8})$$

where HV is heating value per pound of fuel in Btu, C
is percentage of carbon by weight in one pound of fuel,
H and O are similar percentages of hydrogen and oxygen.
This formula assumes that the oxygen already in the fuel
is, in effect, already combined with a suitable amount
of the hydrogen, and hence takes no active part in the
combustion so far as effective heating is concerned.
The values of heat for complete combustion of carbon
(14500) and hydrogen (62100) differ rather materially
from values given by the International Critical Tables
(1) already cited in Table 1. Further, the value for
hydrogen assumes that the H2O produced by combustion is
in _liquid_ form, which cannot be the case, in view of
the temperatures necessary for combustion. The basic
form of this formulae will be employed later in con-
nection with oxygen supply, but will not be used for
computations of heating value. The literature of fuels
gives widely varying values for the heats liberated by
complete combustion for different woods. Hawley and
Wise (4) consider Parr's results best, and they will
be adopted tentatively for this report. The following
table gives Parr's averages, corrected to a dry fuel
basis by Hawley:

TABLE 4
Heating Value of Dry Woods*

Pine......8836   Oak.......8556   Hickory....8448
Cherry....8623   Birch.....8458   Poplar.....8640
       Following estimated from data in (2)
Fir.......8749   Ash.......8725   Elm........8755
* In Btu per lb. of dry fuel.
       Average of 6 Parr values....8594

TABLE 2a

CHEMICAL COMPOSITION AND HEATING VALUE OF
COMMON DRY WOODS

| Wood | Chemical Elements# | | | | | Heating Value* |
	C	H	N	O	Ash	
OAK	50.13	6.02	0.09	43.36	0.37	8316
ASH	49.18	6.27	0.07	43.91	0.57	8480
ELM	48.99	6.20	0.06	44.25	0.50	8510
BEECH	49.06	6.11	0.09	44.17	0.57	8591
BIRCH	48.88	6.06	0.10	44.67	0.29	8586
FIR	50.36	5.92	0.05	43.39	0.28	9063
PINE	50.31	6.20	0.04	43.08	0.37	9153

\# in % by weight per lb. of dry wood; C: Carbon; H:
  hydrogen; N: Nitrogen; O: Oxygen.
* In Btu per lb. of fuel (wood).

Modified from "Elements of Steam and Gas Power En-
gineering", by Potter and Calderwood, p. 30 (values
from determinations by Poole).

FIGURE 6

Weight of Oxygen per cubic foot of air as affected by
Temp.   temperature and humidity

Wt. Oxygen (lbs.)
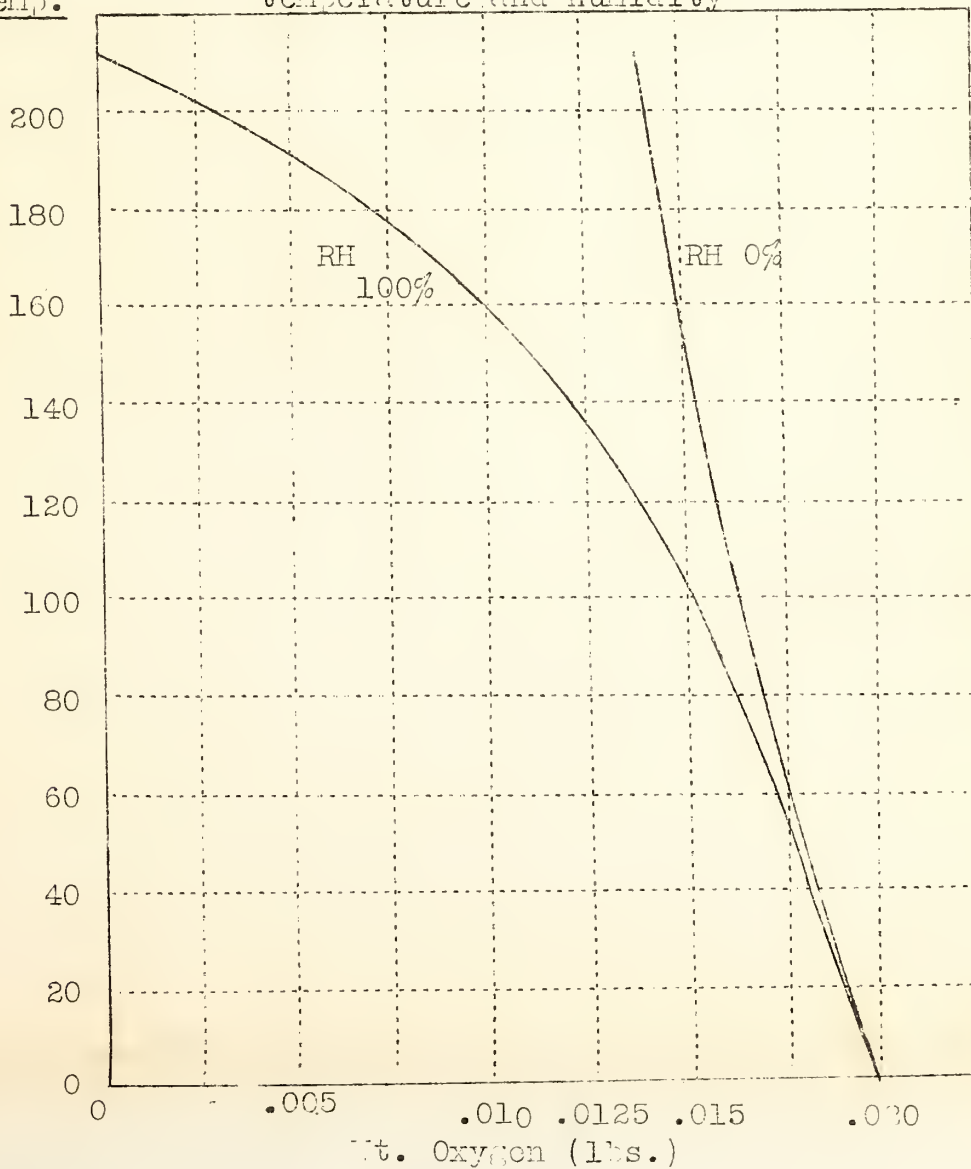
These values are unsatisfactory in the sense
that many species of pine, for example, with differ-
ing resinous material contents, are lumped under one
designation. Satisfactory values for grasses, ferns,
tree mosses, etc. also must be secured before values
adequate for fire hazard rating computations may be
said to be available. There is also the factor of
possible variation in heating values for woods of
the same species but of different ages, different
physiological condition and from different, though
possibly adjoining, areas. However, the foregoing
values will be used tentatively, as illustrating the
method of computation to be developed later in this
report.

Ignition temperatures

Engineering practice assumes certain fixed ig-
nition or kindling point temperatures for each fuel,
that is, temperatures at which active combustion
rather than slow oxidation starts. Temperature is
not the only factor concerned, however. Finely powdered
iron will start burning at a lower temperature than
will iron wire, because it presents relatively more
surface to the oxygen of the air in proportion to the
quantity of material present. This factor of ratio of
surface to volume and mass is operative in forest fires.
Thus, the finer and lighter fuels (grasses, twigs, needles,
etc.) ignite more readily than the coarser and heavier
fuels (stumps, logs, snags, etc.), even though the chem-
ical composition is practically identical. The smaller
the quantity of oxygen present (as affected by air
pressure, for example), the more difficult ignition be-
comes. The vapor of methyl alcohol in air must be raised
above a red heat before combustion starts, but the same
mixture in pocket lighters ignites readily by means of
a thin platinum wire acting as a contact or catalytic
agent without any other source of heat. Thus, strictly,
no definite kindling temperature can be given unless
the other conditions are specified, such as the nature
and condition of the fuel, the amount of oxygen avail-
able, the ratio of surface to volume and mass, the pre-
sence or absence of a contact agent, and its nature.

Wood fuels, upon being heated, evolve volatile
products which ignite at lower temperatures than does
the fixed carbon (charcoal) of the wood substance.

Hence, any fixed ignition temperature assumed for purposes of calculation is really equivalent to an approximate _average_ temperature at which the most ignitable components of a fuel will begin to burn under favorable, if not optimum, conditions.

Hawley and Wise (4) state that the burning of wood involves two general aspects,

1.) The conditions under which wood will ignite and burn, and
2.) Its heat of combustion.

According to these authors, ignition depends on the method and rapidity of heating, the air supply and so far as statement of an actual temperature is concerned, on the place where the temperature of ignition is measured, among other factors. They state that all woods begin to decompose (give off volatile products) at a temperature of about 275 C. or 527 F.; provided the wood is dry. Exceptions occur, however, due to

1.) The physical properties of the wood concerned, such as porosity in its influence on the surface of contact between the wood and air, and

2.) The presence of extractives with low ignition temperatures, such as volatile oils.

They state further that combustion once started continues so long as air supply and heat of combustion are not materially affected, the latter in the sense that the heat evolved is not dissipated, but heats new portions of fuel to the ignition temperature. Chemically, the combustion of wood may be divided into two stages,

1.) Combustion of vapors and gases given off by the exothermal (heat liberating) decomposition of wood.

2.) The combustion of the solid residue of charcoal left behind after the exothermic reaction is completed.

The charcoal appears to act as a catalytic agent in wood combustion. It is important to bear in mind that the outside of a stick can burn at 275 C. without heating the interior above this point, due to radiation and conduction losses to the air.

Koehler (5) describes the ignition and combustion of wood substantially as follows: At 212 F. slight and gradual decomposition begins. At 320F. decomposition is more rapid and the wood has a charred appearance. At 480 F. the wood has the appearance of brownish charcoal, and at 575 F. and higher the charcoal is black and metallic. At 400 C. or 752 F. all woods ignite very quickly, but the lighter woods burn more readily. "Wood" ignites spontaneously at temperatures slightly over 525 F., and sound hemlock has been ignited at 428 F. and decayed hemlock at 406 F. without a pilot flame to ignite the evolved gases.

Various other references, principally engineering handbooks, give ignition temperatures as follows:

Dry Charcoal...............660 deg. F.
Dry Pine Wood..............800 deg. F.
Dry Oak Wood...............900 deg. F.

It is probable that these values are rough averages based upon air dry wood, which may contain 12% or more moisture, or that special conditions of oxygen supply and other factors were involved. In any case, they seem too high in view of the foregoing, and hence will be disregarded. Hawley (6) and Gisborne (7) have taken 540 F. as the approximate ignition temperature for the average dry fuels concerned in forest fires, and this value will be adopted in this report, for use as a reference point in computations.

Species factors and related miscellaneous factors

Average values for density, volume of fuel per unit area, surface area of that volume, ignition point and heating value must be secured or approximated in order for proper evaluation of these factors in fire hazard rating formulae. Such values may most suitably be presented in tabular or graphical form. Quantity and type of fuel may be approximated, apparently, for California at least, from data collected in connection with the cover type map.

Practically the only fuel shapes which must be considered are the cylindrical (twigs, branches, trunks) and flat (deciduous leaves, duff layer, etc.).

Moisture factors

The moisture content of fuels acts to

1.) Prevent contact of oxygen with wood substance.
2.) Increase the amount of heat required for ignition and combustion.

In the first case, contact is prevented, at least partially, so long as the wood contains any water whatever. After being driven off from the wood by heat, the water vapor will add to the amount of water vapor available to displace air and reduce the effective amount of oxygen in that way. In the second case, water in the fuel must be raised to the boiling point, must be vaporized, and the vapor raised to the ignition point, prior to ignition, assuming that water must be entirely removed from any given limited surface before combustion can occur. It appears from experiments by Dunlap, quoted by Koehler (5), that some heat is required to entirely remove the hygroscopic water remaining after ordinary evaporation, ranging from 29.7 Btu for sugar maple to 35.3 Btu for longleaf yellow pine. This heat is necessary to overcome the chemical attraction of the wood substance for the water. According to the International Critical Tables (1), this heat of complete wetting, in Btu per pound of dry fuel (as for the Dunlap values), is 14.6 Btu for powdered cellulose dried in vacuo at 250.8 F. and 28.8 Btu for powdered wood fiber (species not given). Provisionally, this heat of wetting will be taken at 30 Btu per pound of dry material for deciduous species and 35 Btu for the resinous conifers. The wood itself must be raised to the ignition temperature, and this quantity of heat is additive to all of the foregoing.

Hawley (6), using two one pound blocks of wood, identical except for moisture content, calculated the number of Btu required to raise the fuel samples to an ignition temperature of 540 F. from an air temperature of 50 F., under standard atmospheric pressure (29.921") and boiling point of 212 F., as follows:

| Block A (20% moisture) | | Block B (5% moisture) |
Btu	Operation	Btu
160.00	Raising wood to 540 deg. F.	160.00
32.40	Raising water to 212 deg. F.	8.10
193.00	Vaporizing water	48.25
32.80	Raising vapor to 540 deg. F.	8.20
418.20	TOTALS	224.55
258.20	Totals, excluding wood	64.55

From this calculation it is seen that the heats re-
lating to the water in the fuel are proportional to
the fuel moisture contents expressed as percentages,
thus:

$$\frac{64.55}{258.20} = \frac{5}{20} = \frac{1}{4}$$

While other factors apparently must be considered in
determining the amount of heat necessary for ignition,
as will appear later, this calculation shows that
four times as much heat is required to eliminate the
water from Block A compared with Block B, and that, so
far as moisture is concerned, inception hazard is in-
versely proportional to fuel moisture content.

Fuel moisture content

The moisture in fuels may be absorbed from the
air, the soil or through precipitation and condensa-
tion processes, such as rain, snow, dew or frost.
Wood is a complex arrangement of cells, with void
spaces or cell openings in addition to the wood sub-
stance in the cell walls. The cell walls themselves
are capable of holding moisture; this moisture is
termed "fiber" moisture, or hygroscopic moisture. When
the cell walls hold their maximum capacity of moisture
at any given temperature, the "fiber saturation point"
is said to have been reached, and no further changes
in volume (swelling) will take place when additional
moisture is taken up by the cell spaces or voids. Any
drop in cell wall moisture content below the fiber sat-
uration point causes shrinkage of the wood sample. The
moisture taken up by void spaces is termed "free" water.
The moisture in cell walls is absorbed from the air;
moisture in free form in the voids does not occur un-
less the fuel is immersed in water or is directly wetted
by precipitation. When both the cell walls and the voids
are holding their moisture capacity, the wood is said to
be completely saturated. All species tested have been
found to have approximately the same equilibrium fuel
moisture values, by equilibrium being meant the condi-
tion when the wood neither gains nor losses moisture
under any existing conditions of temperature and rela-
tive humidity of the air from which absorption occurs.
Gisborne (7) says: "results of laboratory tests (at
Forest Products Laboratory, Madison, Wisc.) were so
nearly alike for the materials tested that for all prac-
tical purposes the different materials may be said to
have the same equilibrium moisture content for any parti-
cular temperature and relative humidity".

FIGURE 1

Smoothed Average Relations
between
AIR TEMPERATURE, HUMIDITY
AND VAPOR PRESSURE,
and
EQUILIBRIUM FUEL MOISTURE
CONTENT

(Based on tests by Forest
Products Laboratory,
Madison, Wisc.)
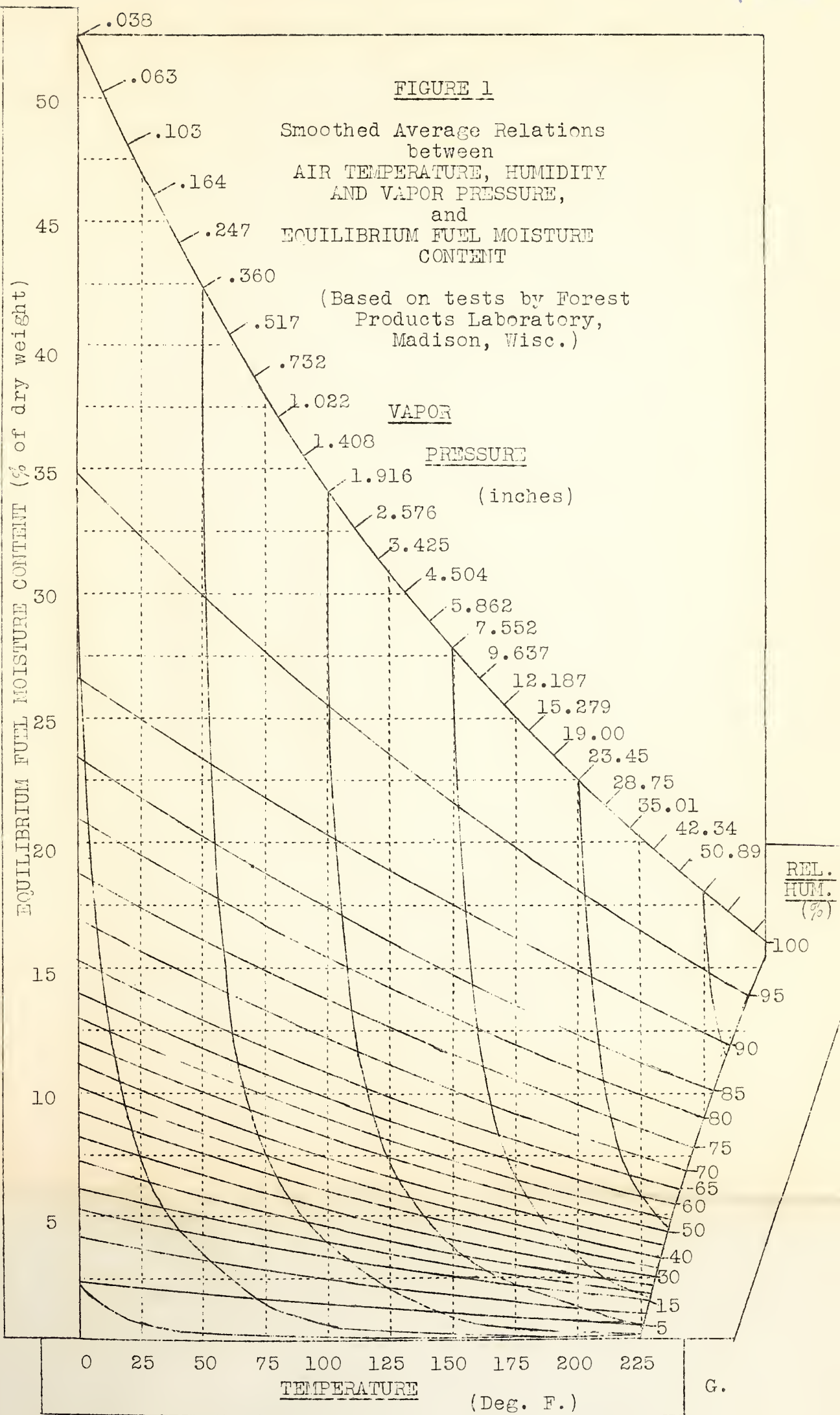
Wood is a colloid, that is, a chemical compound of such nature that it forms a colloidal suspension or solution with water, the wood substance becoming partially converted to a gel in the process, with consequent reduction in strength and increased pliability. The absorption of water by wood, as with other hygroscopic materials, is a complex process. It is probable that there is a chemical solution of water in wood, and that capillarity, surface tension and adsorption are factors involved. There are two explanations for the fact that water is condensed to liquid form in the wood, from the air, without high humidity or appropriate temperature changes. One is that the condensation occurs as the result of very fine capillaries in the wood affecting vapor pressure to such an extent as to cause condensation, and the other is that both wood particles and atmospheric water vapor are electrically charged and the water vapor is attracted and condensed by wood particles of opposite charge. This is the present partial explanation for the phenomenon of adsorption. Moisture thus adsorbed on the wood surface is absorbed by the wood through capillary and surface tension phenomena.

Peck (3) describes the phenomena as follows: "Wood substance, mainly cellulose and lignin, is a hygroscopic material, i.e.-it possesses the power to remove water vapor from the surrounding atmosphere. The water removed is caused to go into solution with wood, forming what might be called a solid solution. In any atmosphere of constant conditions, the process of absoprtion of water by a piece of wood continues until the vapor pressure of the solution is equal to that of the atmosphere. The wood will have then attained what is called an equilibrium fuel moisture content. If the temperature of the atmosphere and wood were raised, water would pass from the wood to the atmosphere, but if the temperature were lowered, the reverse would take place. This means that for a given vapor pressure of the solution, the lower the temperature the greater will be the concentration, or the more water the wood can dissolve."

In general, the properties of colloidal solutions as to boiling and freezing points are not affected as in other solutions, and advantage of this property can be taken in fire weather and fire hazard computations as will appear later.

The relations between equilibrium fuel mois-
ture content, and air temperature, relative humi-
dity and vapor pressure are shown in Figure 1,
adapted from a diagram in (8). The vapor pressure
lines are merely guide lines. A diagram of this
nature is very useful is estimating the effects of
given changes in temperature and humidity on fuel
moisture. While the approach to equilibrium con-
ditions is very slow for heavy fuels, the lighter
fuels (such as the surface layer of duff, grasses,
ferns, mosses, etc.) respond rather rapidly to at-
mospheric changes, with lags varying from about one
hour for fireweed to 3 or 4 hours for the heavier
types of duff. It should be borne in mind, in the
absence of detailed data showing the <u>rate</u> of at-
tainment of equilibrium fuel moisture conditions by
various fuels, that the graph merely indicates the
trend of the change that will occur, and if the
conditions remain constant for a relatively long
time, the values of fuel moisture that ultimately
will be reached under the given conditions.

For example, assuming a fuel moisture of 20%,
relative humidity 85%, temperature 55 F., a point
will be found on the graph lying on the vapor pres-
sure line for .360". If the temperature is raised
to 75 F., with vapor pressure constant (no im-
portation or exportation of moisture), the new equi-
librium value towards which the fuel moisture will
tend is found by tracing down the vapor pressure line
.360" to its intersection with 75 F., which point shows
a fuel moisture of 7.5%. With these same conditions,
lowering the temperature to 50 F. would result in a
fuel moisture of 42.5%. The graph shows the equili-
brium fuel moisture at any temperature and humidity
(within its range), and the changes produced by
varying temperature or humidity, or both. Table 5
shows actual values obtained from various sources
and smoothed to a degree apparently justified by
theoretical considerations.

The experimental values on which Table 5 and
Figure 1 are based are faulty in the sense that the
duration of the tests was not sufficient to insure
that equilibrium values were reached for the higher
humidities. Why this is so will be evident from the
facts that a good sized white pine log, perfectly dry,
would have to be immersed in water for more than five
years to soak up its capacity of water (9) and that
Douglas fir sticks 4"x8"x6' were not fully saturated
after seven years submersion (5). McKenzie (4) found

TABLE 5

EQUILIBRIUM FULL MOISTURE CONTENT*
IN RELATION TO
AIR TEMPERATURE AND RELATIVE HUMIDITY
(for wood)

Rel. Hum. %	Temperature (deg. F.)							
	0	32	50	75	100	125	150	212
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	2.4	2.0	1.8	1.6	1.4	1.2	1.0	0.7
10	4.2	3.6	3.4	3.0	2.7	2.4	2.0	1.4
15	5.3	4.5	4.2	3.8	3.4	3.0	2.6	1.8
20	6.3	5.4	5.0	4.5	4.0	3.5	3.1	2.2
25	7.4	6.3	5.8	5.2	4.6	4.1	3.6	2.6
30	8.3	7.2	6.6	5.9	5.3	4.6	4.1	2.9
35	9.2	8.1	7.5	6.7	6.1	5.3	4.7	3.4
40	10.2	9.0	8.4	7.5	6.8	6.0	5.3	3.8
45	11.1	9.8	9.2	8.3	7.5	6.8	6.0	4.4
50	12.0	10.7	10.0	9.1	8.2	7.5	6.7	5.0
55	13.0	11.6	10.9	9.9	9.0	8.2	7.3	5.6
60	14.0	12.5	11.8	10.8	9.8	9.0	8.0	6.2
65	15.3	13.8	13.0	11.9	10.8	9.9	8.9	7.0
70	16.9	15.3	14.4	13.2	12.1	11.1	10.1	7.9
75	18.8	17.0	16.0	14.8	13.6	12.4	11.3	9.0
80	21.0	19.0	18.0	16.7	15.4	14.1	12.9	10.4
85	23.4	21.4	20.2	18.8	17.4	16.0	14.9	11.9
90	26.5	24.5	23.4	21.8	20.3	18.9	17.5	14.2
95	35.0	31.7	30.0	27.7	25.5	23.5	21.6	17.3
100	52.5	45.8	42.4	38.0	34.1	30.8	27.7	21.3

* Graphically smoothed averages from Forest Products Lab.
Technical Note D-5 (averages at 70 deg. F. for 5 species
by M. E. Dunlap, averages at 212 deg. F. for 9 species
by H. E. McKenzie, and value at 54 deg. F. for spruce
by H. E. McKenzie), considered in relation to graphs of
values in references (11) and (8), and criticism of values
by Hawley and Wise (4).

that spruce blocks 1"x1"x6" held at 12 C. and
100% relative humidity took up 43.2% moisture in 79
days and that absorption was still taking place
slowly.

In California, systematic fuel moisture meas-
urements are not made. In view of the importance
of fuel moisture, such measurements are essential
to proper fire hazard rating. If not actually
measured, there must be developed a formula for
computing the fuel moisture content for any fuel
at any time and place, through the use of detailed
weather records (which are systematically kept) and
their application to a formula expressing evapora-
tion losses and condensation gains. Such a formu-
la is now being developed, but is not presented
here because the factors affecting the evaporation
of moisture from woods as distinct from free water
surfaces require additional study. So far as can
be foretold at present, the formula seems suitable
for the purpose of calculating fuel moisture con-
tents for broad cover type classifications. The
nature of the seasonal fuel moisture curve, show-
ing fairly rapid changes for lighter fuels, but
slow changes for heavy fuels, and with but little
change of a cumulative nature from day to day, due
to short duration of high temperatures and low humi-
dities, tends to make the formula approximations
of satisfactory accuracy. This formula will be made
the subject of a separate report when completed.

Heat factors

As already indicated, the wood must be raised
from its actual temperature to the ignition point
before active combustion can start. The computations
required involve a fairly accurate knowledge of the
specific heat of wood. Data are not plentiful. Tests
of 16 species by F. Dunlap (10) for a range of tempera-
ture from 0 C. to 106 C. resulted in a mean specific
heat for all species of .327, this value applying to
the mean temperature of 53 C. or 127 F. The value at
0 C. or 32 F. was found to be .266. There was very
little difference between species or for woods origi-
nating in various localities. Dry samples were used
in the tests. Kent's Mechanical Engineers' Handbook
gives values ranging from .467 to .650, but no defi-
nite particulars are given as to the conditions under
which the tests were made. It seems likely that these
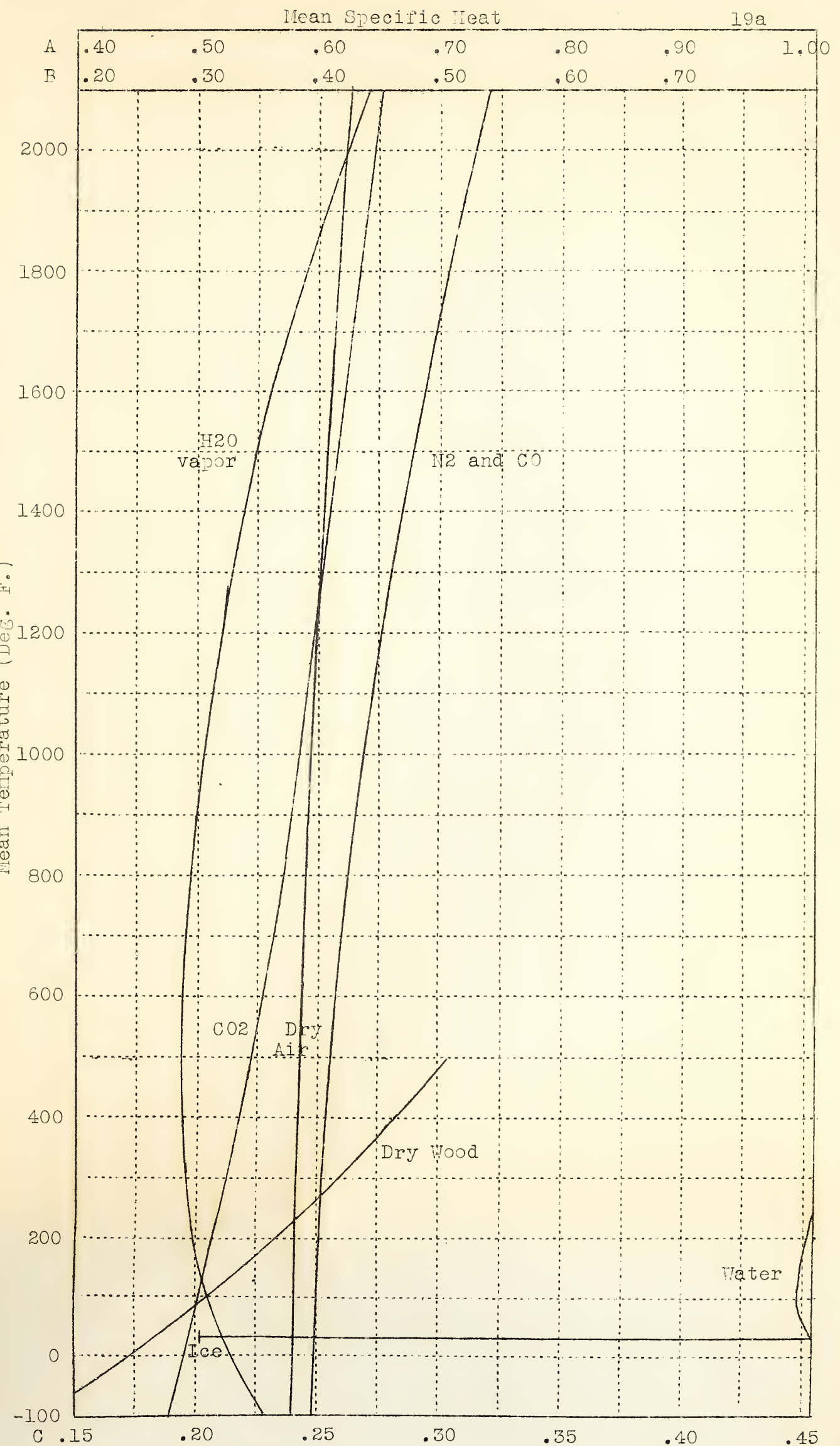
FIGURE 2 - Mean Specific Heats, in Btu per deg. F.
Scale A for water, ice and water vapor; Scale B for dry
wood; Scale C for dry air, N2, CO and CO2.

values were for wood containing considerable moisture
and therefore will not be used. Dunlap's tests indi-
cated appreciable variation with temperature. It
should be noted that Figure 2, giving curves for the
mean specific heat of wood and other substances in-
volved in combustion, uses mean temperatures. In other
words, if the mean specific heat of wood for a tempera-
ture range from 40 to 540 F. is required, first find
the mean temperature from the relation

$$\frac{40 + 540}{2} = 290$$

and then, using this temperature as an argument, a
value of about .406 is found from the curve for the
mean specific heat over this temperature range, per
degree. To then find the total amount of heat re-
quired to raise the wood sample (weight one pound)
to 540 F. from 40F., the following relation is used

$$W(540-40).406 = 203 \text{ Btu}$$

where W is weight of wood (dry) in pounds. All speci-
fic heats used in this preliminary report are those
for constant pressure (cp), since most of the reactions
of importance may be considered to take place under
atmospheric pressure (approximately constant during
reaction). No allowances are made for pressures less
than one atmosphere (as due to altitude, for example),
since values are not much changed unless pressure dif-
ferences are pronounced (1).

Ignition temperatures and heating values have al-
ready been discussed. The standard (1) values for the
heats involved in changes of state of fuel moisture, in
heating wood, in heating air and products of combustion,
in vaporizing water and heating the vapor are as follows:

TABLE 7

Standard Values for Heat Constants

Material	State	Process	Heat*
Water	Solid (ice)	heating	0.502
Water	Solid (ice)	melting	143.5
Water	Liquid	heating	1.000
Water	Liquid	vaporization	Table 6
Water	Liquid	boiling point	Table 6
Water	Vapor	heating	Fig. 2
Wood	Solid	heating	Fig. 2
Wood	-----	ignition	540 F.
Wood	-----	heat of formation	Table 4
Wood	Solid	heat of wetting	30 to 35
Products of comb	Gaseous	heats of formation	Table 1
Products of comb	Gaseous	heating	Fig. 2

* Btu unless otherwise noted.

TABLE 6
Relations Between Elevation, Standard* Atmosphere,
Boiling Point and Heat of Vaporization

Elev. above sea level in feet	Approx. Air Pressure in inches	Boiling Points deg. F.	Heat of Vaporization in Btu#
-2000	32.15	215.7	968.7
-1500	31.58	214.8	969.2
-1000	31.02	213.8	969.9
- 500	30.48	212.9	970.5
0	29.921	212.0	971.2
500	29.38	211.0	971.7
1000	28.86	210.1	972.2
1500	28.32	209.2	972.8
2000	27.82	208.3	973.4
2500	27.30	207.4	973.9
3000	26.81	206.5	974.5
3500	26.31	205.6	975.1
4000	25.84	204.7	975.7
4500	25.35	203.7	976.3
5000	24.89	202.8	976.9
5500	24.41	201.9	977.5
6000	23.98	201.0	978.0
6500	23.49	200.1	978.5
7000	23.09	199.2	979.1
7500	22.63	198.2	979.7
8000	22.22	197.3	980.3
8500	21.80	196.4	980.8
9000	21.39	195.5	981.4
9500	20.98	194.6	982.0
10000	20.58	193.7	982.6
10500	20.18	192.8	983.1
11000	19.79	191.8	983.7
11500	19.40	190.9	984.3
12000	19.03	190.0	984.9
12500	18.64	189.1	985.4
13000	18.28	188.1	986.0
13500	17.92	187.2	986.5
14000	17.57	186.3	987.1
14500	17.21	185.4	987.7
15000	16.85	184.4	988.3

Btu: British thermal units, defined at 60 F.
* Standard atmosphere as adopted by the National Advisory Committee for Aeronautics, with specifications as follows: Sea level pressure 29.921"F.
Sea level temperature 59 F.
Temperature gradient 0.003566 F. per ft.
Temperature in stratosphere -67 F.
Altitude at base of stratosphere 35,332 Ft.
The air is a dry, perfect gas.

For the curve of mean specific heat of dry wood in
Figure 2, Dunlap's values were used as two points on
the curve, and since wood decomposes gradually with in-
creased temperature (evolving volatile materials and
becoming practically pure carbon or charcoal), the mean
specific heat of carbon at 870 F. was taken from the
International Critical Tables (1) as a third point on
the curve. The result is plotted in Figure 2.

DERIVATION OF FORMULAE

The foregoing preliminaries disposed of, the fol-
lowing discussions will indicate the methods used and
attempted to secure mathematical expressions of the
various factors involved in fire hazard rating, and to
combine factor expressions into general formulae. This
work is not complete, but is believed to be suggestive
of general method. In some cases, the mathematical
formulae derived can be said to be in definite and final
form. In developing the formulae, the additional dis-
cussion required for adequate understanding of the ef-
fects of modifying influences, not covered in the fore-
going, and the discussion necessary to clarify methods,
define units and indicate assumptions, will appear
wherever it seems needed.

Fundamental bases

Tentatively, the unit of fuel considered will be
a cube with a density corresponding to that for pure
wood substance (1.47) to which all types of fuel will
be referred. The cube will be considered to be freely
suspended in air containing no appreciable foreign
materials (dust, smoke particles, etc.) and no products
of combustion as such. The system of units used will
be English, with lengths in feet and miles, time in
seconds, areas in square feet and square miles, volumes
in cubic feet, weights in avoirdupois pounds (later tons),
temperatures in degrees Fahrenheit, barometric and vapor
pressures in mercurial inches and heats in British ther-
mal units, defined at 60 F. Table 8 on page 21a lists
the symbols employed in the formulae. Since many con-
tain more than one letter, it should be understood that
mere juxtaposition of symbol letters does not neces-
sarily indicate multiplication, as in ordinary mathe-
matical formulae. To indicate this operation, spaces usually
are left between symbols containing more than one letter.
Hazard of fire inception and translation will be consid-
ered partially, but only inception hazard will be developed
to a degree warranting the statement of a formula of
general type. It is assumed that wood substance is not
heated until all water is driven off, and that ignition
cannot be accomplished similarly until the wood is "bone"
dry, in both cases considering a limited surface only.

TABLE 8
Symbols used in Formulae.

Ab: area burning surface, or fire area, square feet.

Ac: cross sectional area of "smoke" column, sq. ft.

Aes:exposed surface fuel area, square feet, also sq.mi.

a: acceleration; also a fire dimension, parallel to prevailing wind.

B: air pressure in general, inches of mercury.

Ba: total air pressure, inches.

Bv: vapor pressure.

Btu: British thermal unit, a measure of heat quantity, defined at 60 F.

C: carbon.

C%: percentage by weight of carbon per pound of dry fuel.

C.: Centigrade.

CO: carbon monoxide.

CO2: carbon dioxide.

Cf: circumference of fire (perimeter) in feet.

cos: natural trigonometric cosine of an angle.

cp: constant pressure.

Da: density of air (any units, commonly weight in lbs. per cu.ft. or in grams per liter).

Dc: density (virtual) of mixture of gases in "smoke" column.

Df: true oven dry density of fuel, referred to the weight of pure water (62.428 lbs.) per cu.ft. at its maximum density (4 C. or 39.2 F.).

E: eddy or whirl.   F.:Fahrenheit.

FM%: fuel moisture percentage (% given by weight of water divided by oven dry weight of wood).

g: acceleration of gravity, 32.174 ft. per sec. per sec.

G: slope angle between ground and horizontal.

G%: same, but in percent of grade.

G: gram weight.

Hf: heat of fusion (melting), Btu, per lb. ordinarily.

Hv: heat of vaporization, Btu, per lb., ordinarily.

HI: hazard of fire inception in relative units.

HVi: effective heating value of any given ignition agent, in Btu.

HF: heat of formation in Btu per lb., ordinarily.

H: hydrogen.

H%: percentage by weight of hydrogen per lb. of dry fuel.

H2O: water, liquid or vapor.

HV: heating value in Btu, total or per lb. of dry fuel.

HIG: heat required for ignition, total; total or per lb. of dry fuel.

Hw: heat of wetting, in Btu per lb. of dry fuel.

I: indraft in general.

K, k, k1, k2: constants.

mm.: millimeters.

N2: nitrogen.

O: oxygen.

O%: percentage by weight of oxygen per lb. of dry fuel.

RH: relative humidity %.

R: resultant.

s: slope angle between "smoke" column and horizontal.

s%: same, but in % grade.

sin: natural trigonometric sine of an angle.

SHf: mean specific heat of fuel, in Btu per lb. per deg.

SHs: mean specific heat of solid (ice) as above.

SHw: mean specific heat of liquid water, as above.

SHv: mean specific heat of water vapor, as above.

SHa: mean specific heat of air, as above.

T: temperature in general, absolute or Fahrenheit. If absolute, expressed by 459.6 or 460 ÷ T (Fahrenheit).

Ta: air temperature, Fahrenheit degrees.

Tw: temperature of fuel moisture or water; F.

Tb: temperature of boiling point of water, F.

Ts: temperature of solid (ice), F.

tan: natural trigonometric tangent of an angle.

Ti: ignition temperature, F.

Tf: fuel temperature, actual, F.

Tm: temperature of melting point of ice, F.

Tc: temperature of "smoke" column at its base, F.

Vwi: fire-produced indraft wind velocity, feet per sec.

Vwp: outside prevailing wind velocity, undisturbed by fire-produced indrafts, in feet per sec.

Vws: velocity of wind parallel to a slope, feet per sec.

Vwa: corrected wind velocity as indicated by a cup anemometer, ft. per sec.

Vpc: volume of products of combustion, cubic feet, or combustion layers of cross section equal to fire area and depth y.

Vf: volume of fuel, cu.ft.

Va: volume of air, cu.ft.

Vv: volume of vapor, cu.ft.

VP: vapor pressure, inches, in general.

Vr: a resultant velocity in ft. per sec.

Vc: vertical component of ascent velocity of "smoke" column, ft. per sec.

Vw: horizontal or slope component of "smoke" column, wind, or wind velocity in general, in ft. per sec.

Vw: a rate of air supply, based on wind velocity, but including effects of fire shape, size, ground slope, corrected anemometer reading and depth of combustion layer y.

Vmph: velocity miles per hour. Vfps: velocity feet per sec.

Wacc: weight of air required for complete combustion, total or per lb. dry fuel.

Wfo: weight of fuel oxygen, total or per lb. dry fuel.

Wo: weight oxygen, in general, lbs. per cu.ft. of air.

Wa: weight of air, as above, dry or moist.

Wf: weight of fuel, dry, lbs. or tons.

Ww: weight of fuel moisture or water (any form), lbs.

W: wind in general.

x: a cross sectional dimension of the "smoke" column parallel to the prevailing wind, feet; also indicates multiplication.

y: thickness (ft.) of air layer adjacent to burning surface in which combustion is active.

z: fire dimension at right angles to prevailing wind, ft.

The amount of heat required for ignition

Hawley's calculation given on page 15 apparently does not include all of the principal factors involved. To cause one pound of standard wood fuel to ignite, assuming a fixed ignition point temperature of 540 F., requires the following:

1.) Heat to raise dry wood from its actual temperature to the ignition temperature.

2.) Heat to drive off all fuel moisture. If in the form of ice, the successive stages are

      a.) Heat ice to melting point.
      b.) Melt ice.
      c.) Heat water from melting point to boiling point.
      d.) Vaporize water.
      e.) Heat vapor to ignition point.

If the fuel is already above the freezing point, and the fuel moisture is consequently liquid water, the ice stages A. and b. need not be considered, and the actual temperature of the water instead of the melting point is considered in stage c.

      f.) Heat to overcome the chemical attraction between the wood and water, approximately 30 Btu per pound of dry hardwood and 35 Btu for conifers (from values by Dunlap and from the International Critical Tables), termed the "heat of wetting".

3.) Heat required to raise the air needed for combustion from its actual temperature to the ignition temperature. Obviously, the chemical combination between the fuel substances and the oxygen of the air does not occur in the sense of active combustion until the ignition point is reached; both the fuel substances and the oxygen must attain this temperature if the ignition temperature is to be maintained during combustion and not merely for an instant at the start of combustion; and since the oxygen is thoroughly mixed with other elements (principally nitrogen) in the air, the whole air mass must be heated and not the oxygen alone.

Obviously, one pound of wood does not necessarily represent the real unit involved in ignition, especially for different igniting agents, which may vary from very small surfaces (practically points) to rather extensive areas (as with ignition by radiated heat). The <u>relative</u> amounts of heat involved remain unchanged regardless of the fundamental unit adopted. The pound is used because it is the most convenient unit for computations.

The amount of heat required to raise any substance through any temperature range is given by the general relation:

1) Weight substance(final temp. - initial temp.) mean specific heat of substance per degree = am't. heat.

The amount of heat is expressed in Btu if weights are in pounds, temperatures in degrees Fahrenheit and mean specific heats in Btu per degree.

From the foregoing equation and the discussion on page 22, using symbols as on page 21a, the total heat (HIG) required for ignition of standard dry wood fuel (of composition as in Table 8) is expressed by the relation:

2) $HIG = Wf \left[SHf(Ti-Tf) + Hw \right] + Ww \left[SHs(Tm-Ts)+Hf+ SHw(Tb-Tw)+Hv+SHv(Ti-Tb) \right] + SHa(Ti-Ta)Wa$

The relative hazard of fire inception obviously is inversely proportional to the amount of heat required for ignition, other factors the same, or

3) $HI = \dfrac{1}{HIG}$ and other factors.

It is apparent that all igniting agents acting through flame or glowing sparks, rather than mere heat, are subject to the identical conditions that govern fire behavior. Under certain conditions, an igniting agent may be ineffectual due to its inability to deliver a sufficient amount of heat per unit time per unit fuel area, over and above losses of various sorts. It seems possible to definitely evaluate the relative fire inception power of various igniting agents under different conditions, if suitable provision can be made for heat lost by radiation, conduction and convection, and for the total heating value as well as the rate of combustion of the materials composing the igniting agent. Assuming that this can be done, the effective heating value of the igniting agent (HVi) affects formula 3 as follows:

4) $HI = \dfrac{HVi}{HIG}$ and other factors.

In other words, if the effective heat produced by the igniting agent is less than that required for ignition, a low hazard exists; if HVi is equal to HIG, unit hazard occurs, and if HVi is greater than HIG, a hazard greater than unity occurs. This report, however, will

not attempt rating of igniting agents. This matter
will be deferred to later progress reports.

The amount of heat produced by complete combustion

This is merely the total heating value of a given
quantity of a given fuel, the unit value being based
on careful calorimeter measurements. Given types of
fuel may be considered to have certain average heating
values (dry), sufficiently accurate for fire hazard
rating purposes, where other possible sources of error
are many. The amount of heat produced by combustion
(HF) is expressed by

5) $HF = Wf(HV)$

for complete combustion and lesser values in proportion
to the completeness of combustion and the nature and
amount of products formed.

Some of the HF is utilized in driving off fuel
moisture, some heats the fuel, some heats the soil,
some heats air for combination with fuel, some heats
the products of combustion and some is radiated to ob-
jects at a distance. After the igniting agent has
expended its store of heat and has started combustion,
the HF must be so dissipated that the fuel adjacent to
the surface actually burning is kept continuously at or
above the ignition temperature. It is apparent that
the characteristics of the substances and the processes
involved must be considered in some detail, and that the
rate of evolution of the heat (directly proportional to
the speed of the reaction) must be considered also in
determining the relative heat losses by radiation, con-
duction and convection. Only a part of this problem
will be discussed later in this report; further attack
will be postponed to further progress reports.

The amounts of air required for combustion

Dulong's formula for the heating value of given
fuels has the general form:

6) HV or HF $= Wf \left[k_1 C\% + k_2 (H\% - \dfrac{O\%}{8}) \right]$

when a part of the hydrogen in the fuel is considered to
be already, in effect, combined with fuel oxygen. The
Dulong relation uses values of 1 and 16, respectively, for
the atomic weights of hydrogen and oxygen. More accurate-
ly, the atomic weight of hydrogen is 1.0077, which makes
the divisor of the oxygen percentage about 7.94 instead
of 8. With this correction, the Dulong formula can be
used to calculate the amounts of air required for com-
bustion, by substituting suitable values from Table 1
for the constants k_1 and k_2.

From Table 1, 7.94 lbs. of oxygen are required for complete combustion of one lb. of hydrogen, and 2.67 lbs. for one lb. of carbon. When combustion of the latter is incomplete, only 1.33 lbs. of oxygen are required. As will be shown later, oxygen constitutes .23197766 lb. in each pound of dry air free from foreign materials and not mixed with products of combustion. Assuming perfect contact of air with fuel, the weights of dry air required for combustion per pound of combustible, are as follows:

7) Wa (for H) $= \dfrac{7.94}{.23197766} = 34.23$ lbs. (H2O product)

8) Wa (for C) $= \dfrac{2.67}{.23197766} = 11.50$ lbs. (CO2 product)

Foregoing for complete combustion.

9) Wa (for C) $= \dfrac{1.33 plus}{.23197766} = 5.75$ lbs. (CO product)

Foregoing for incomplete combustion.

The density of air of any moisture content, when referred to dry air under standard conditions as unity, is given by

10) $Da = \dfrac{6.215(2.643Ba-Bv)}{459.6 + Ta}$

According to the International Critical Tables (1) and Humphreys (11) the weight of dry air under standard conditions is .08072 lbs. per cu.ft. The weight of dry air under any conditions of temperature, pressure and relative humidity is given by the equation

11) $Wa = \dfrac{.08072(491.6)(Ba-Bv)}{29.921 (459.6 + Ta)}$

which simplifies to

12) $Wa = \dfrac{1.32625(Ba-Bv)}{460 + Ta}$

since the volume of dry air in a unit volume of moist air mixture is given by

13) $Va = \dfrac{Ba-Bv}{Ba}$

and the volume of water vapor, similarly, by

14) $Vv = \dfrac{Bv}{Ba}$

The volume of moist air required for complete combustion is expressed by the following equations, since the volume is given by total weight of dry air required divided by the weight of dry air per cubic foot of mixture:

15) V_a (for H) $= \dfrac{34.23(460+T_a)}{1.32625(B_a-B_v)} = \dfrac{25.814(460+T_a)}{B_a-B_v}$

16) V_a (for C) $= \dfrac{11.50(460+T_a)}{1.32625(B_a-B_v)} = \dfrac{8.673(460+T_a)}{B_a-B_v}$

when combustion is complete, and

17) V_a (for C) $= \dfrac{5.75(460+T_a)}{1.32625(B_a-B_v)} = \dfrac{4.386(460+T_a)}{B_a-B_v}$

when combustion is incomplete. The foregoing give values for each pound of combustible. Using Dulong's formula, values for a given fuel of known chemical composition are given by the following equations:

18) $W_a = W_f\left[34.23(H\% - \dfrac{O\%}{7.94}) + 11.50C\%\right]$

for complete combustion, and

19) $W_a = W_f\left[34.23(H\% - \dfrac{O\%}{7.94}) + 5.75C\%\right]$

for incomplete combustion, a part of the oxygen used in combustion in each case being supplied from the fuel.

20) $V_a = W_f(460+T_a)3.239\dfrac{(7.94H\% - O\% + 2.67C\%)}{B_a-B_v}$

(Complete combustion)

21) $V_a = W_f(460+T_a)3.239\dfrac{(7.94H\% - O\% + 1.33C\%)}{B_a-B_v}$

(Incomplete combustion)

The substitutions on which equations 18 to 21 are based involve equations 6, 12, 15, 16 and 17.

If $\boxed{V_w}$ is the true wind velocity in feet per second, then the weight or volume of air supplied in unit time is given by

22) Total W_a or $V_a = \boxed{V_w}(W_a$ or $V_a)$

Oxygen supply

It has been suggested by Hawley (6) and again by Gisborne (7) that differences in oxygen supply as af-

fected by displacement of air through the action of
water vapor and products of combustion may affect fire
behavior materially, and that further investigation of
this matter is desirable to determine its importance.
The following analysis attempts to definitely evaluate
the oxygen supply factor in extension of the air sup-
ply discussion already given.

Factors

The factors controlling oxygen supply, so far as
practical fire hazard rating is concerned, may be listed
as follows:

The effective oxygen supply is dependent on
1.) The amount of oxygen per unit air volume.
2.) The rate of supply of unit air volumes.
3.) The degree of effective contact between
the oxygen and burning fuel surfaces.

1.) The amount is affected by
a. Air density-controlled primarily by
temperature and pressure.
b. The percentage of oxygen in air-con-
trolled by the displacement of air
by water vapor and foreign materials
already in the air, the nature of the
air mixture and displacement by pro-
ducts of combustion (H2O, N2, CO, CO2,
heat and smoke particles).

2.) The rate of supply is dependent on
a. Number of unit volumes supplied in unit
time-controlled by indrafts produced
through the temperature differential
between gases in contact with burning
fuel surfaces and outside air, and by
general prevailing wind movement or
velocity.

3.) The contact with fuel is affected by
a. The ratio of exposed (burning) fuel
surface to oven dry fuel volume, de-
termining the area in contact with air,
which for unit volume becomes simply the
surface area, and
b. The ratio of exposed surface to mass
or quantity of fuel, since various woods
have different gross densities, and
therefore differing amounts of wood sub-
stance are exposed to air contact per
unit surface area.

FIGURE 2a
WEIGHT OF OXYGEN PER CUBIC FOOT OF AIR
(slanting lines) in percentages of weight (0.02 lbs.)
at 2 deg. F. and 30" net air pressure.
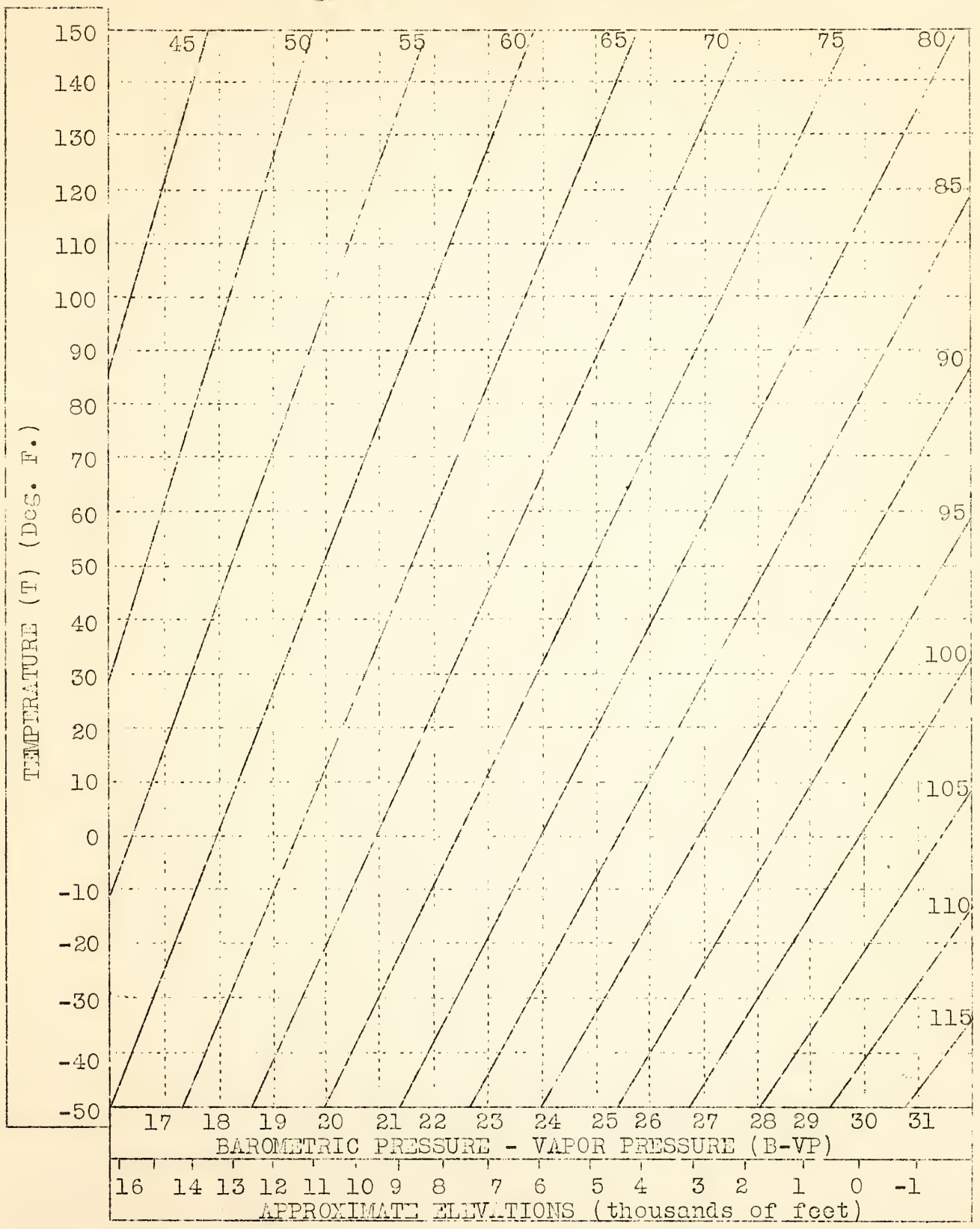
        c. Fuel moisture content- assuming that
        any water in fuel prevents contact
        with air until driven off by heat.

Amount

According to the International Critical Tables
(1) and Humphreys (11), the oxygen in the air is
merely mechanically mixed with other gases and is
not chemically combined with them (other than a
small amount of CO_2) in any way. Oxygen amounts to
20.99% by volume in dry air. The percentage varia-
tion with altitude is negligible for practical pur-
poses, being nearly constant (for dry air) below
about 36,000 ft. Reference (1) gives densities for
dry air and oxygen under standard conditions (tem-
perature 32 deg. F., pressure 29.921" and relative
humidity 0%) as follows:

DRY AIR: 1.293 g. per liter or .08072 lbs. per cu.ft.
OXYGEN: 1.429 g. per liter or .08921 lbs. per cu.ft.

If the value for dry air represents unit density,
then oxygen has a density relative to dry air, as
given by

$$\frac{1.429}{1.293} = 1.1051818$$

and the percentage of oxygen by __weight__ per unit volume
of dry air is given by

$$20.99 \times 1.1051818 = 23.197766\%$$

This percentage is equivalent to .018725237 lbs. of
oxygen per cubic foot of standard dry air. In ac-
cordance with the gas laws (assuming that the air and
oxygen behave strictly as perfect gases, which they
do practically at ordinary temperatures and pressures),
the density of air (or oxygen) varies inversely with
the absolute temperature and directly with the pressure,
and hence the weight per cubic foot of dry air under
any conditions of temperature and pressure may be ex-
pressed by the equation:

23) $W_o = \dfrac{.018725237(491.6)B_a}{29.921(459.6+T_a)}$

Fahrenheit temperatures being expressed on the abso-
lute scale by the addition of 459.6, which is the
equivalent of the value for absolute zero (-273.13)
given by Humphreys (11), converted to Fahrenheit zero.
Equation 23, simplified, becomes:

24) $Wo = \dfrac{.3076543Ba}{459.6+Ta}$

The volume of water vapor and of air present per cubic foot of moist air mixture has already been expressed by equations 13 and 14. Since water vapor is not dissociated into free (chemically uncombined) hydrogen and oxygen except at very high temperatures (only 1.8% dissociation at 3600 F.), for practical purposes it may be considered to displace an equivalent volume of dry air, and hence reduce the amount of oxygen per unit volume of moist air mixture. The formula for Wo per cubic foot of air mixture under any practical conditions of temperature, pressure and relative humidity becomes

25) $Wo = \dfrac{.3076543Ba(Ba-Bv)}{Ba(459.6+Ta)}$

which simplifies to

26) $Wo = \dfrac{.308(Ba-Bv)}{460+Ta}$

with a more than sufficient degree of practical accuracy. Figure 2a on page 27a is a graph of this equation. From this figure, it is evident that at a temperature of 80 F. and net pressure of 30" at sea level, that the relative amount of oxygen per cubic foot of air is 85.5%, and that under the same conditions of temperature and relative humidity but at an elevation of 6000 ft. the relative amount of oxygen is 68.5%. Other things being equal, it may be said that the rate of the combustion reaction (and of fire spread) varies directly with oxygen supply; hence $\dfrac{\text{sea level } 85.5\%}{6000 \text{ ft.} 68.5\%} = 125\%$, nearly,

which means that a fire at sea level would burn 25% faster than one at 6000 ft. under the same conditions except for oxygen supply. Similar calculations can be made for any other conditions or levels.

Foreign materials already in the air (prior to combustion) may consist of dust particles, fog and cloud water droplets, or rain drops and snow flakes, among others less consequential. The atmospheric water vapor has already been taken care of in the Wo formula, and while the percentage of CO_2 fluctuates slightly, the range is not consequential in affecting air density. In general, foreign materials constitute such a very small proportion of the air mixture that they can be disregarded. This is demonstrated by a calculation based on a table by Humphreys (11, page 267) from which it is found that the volume of air displaced by falling rain during a cloudburst (temp. 0 C., pres. 740 mm., rate of precipitation approximately 4" per

hour) would amount to but .00000054 cu. ft. per
unit air volume. Hence all corrections for the pre-
sence of foreign materials other than water vapor
and products of combustion may be disregarded.

The products of combustion (H2O, N2, CO, CO2,
smoke and heat) must be considered, however. All
of the gases produced by combustion are incombusti-
ble (except CO when combustion is incomplete). The
oxygen in the products is chemically combined and
is of no further importance in affecting combustion
except by air displacement. It may be questioned
whether the smoke particles (fragments of unburned
fuel, principally carbon) are sufficient in number
and large enough in size to affect air displacement
materially; and certainly not more important than
the cloudburst calculation already cited (dense
fog is less consequential). Therefore, it seems
reasonable to suppose that it is only the purely
gaseous products of combustion that importantly
affect air displacement. The heat produced by com-
bustion results in decreased density of nearby air
masses and consequently less available oxygen per
unit volume.

At the start of combustion, the burning surface
is at the ignition temperature, and the air necess-
arily must be heated to this temperature prior to
the combination of its oxygen with fuel constituents.
After combustion is under way, however, due to the
surplus heat released by the combustion process, the
burning surface may have a very much higher tempera-
ture. There thus enters the question of the proper
temperature to use in the oxygen supply formulae;
this temperature, apparently, is that of the burning
surface.

It will be necessary, therefore, to secure a
formula expressing the temperature of the burning
surface under various conditions, and substitute it
for Ta in the oxygen formulae, in order to adapt the
latter to actual combustion conditions. This burning
surface temperature is approximately equivalent to
the temperature at the base of the column of ascend-
ing products of combustion (the "smoke" column), and
a formula for determining this temperature Tc will
be given later.

Since wood will not burn until all water is driven
from a given limited surface, the question of displace-
ment of air by fuel moisture becomes a question of the
amount of water vapor added to the products of combus-

FIGURE 3

RELATIONS BETWEEN FIRE AREA AND PERIMETER

tion by the fuel moisture, continuously being driven
off from wood not burning,so long as combustion con-
tinues, first, by heat from the igniting agent, and
later, by combustion itself. Thus, the moisture is
of no practical effect on air displacement until
vaporized and added to the "smoke" column, and simi-
larly has no effect on degree of contact of air and
fuel, since where the fuel is actively burning, there
is no fuel moisture.

Figure 5 on page 11a shows how the amount of
oxygen per cubic foot of air varies with temperature
and relative humidity, pressure constant. For air
of 100% relative humidity; the oxygen supply becomes
zero at the boiling point, since at this point nothing
but water vapor is present and the vapor pressure
equals the air pressure. When the relative humidity is
zero, however, the oxygen supply decreases at a slower
and slower rate with increasing temperature, approaching
zero at an infinitely high temperature.

The displacement of air by the products of com-
bustion may be regarded as a proportional mixing pro-
cess, that is, a given number of unit volumes of
products (at the product temperature) are mixed with
some other number of unit volumes of air, and for the
total number of volumes of mixture, the oxygen will
represent some definite proportion. The following
figures illustrate the considerations employed in the
development of an air displacement coefficient for
application to the oxygen or air supply formulae al-
ready given:

Level ground   Sloping ground
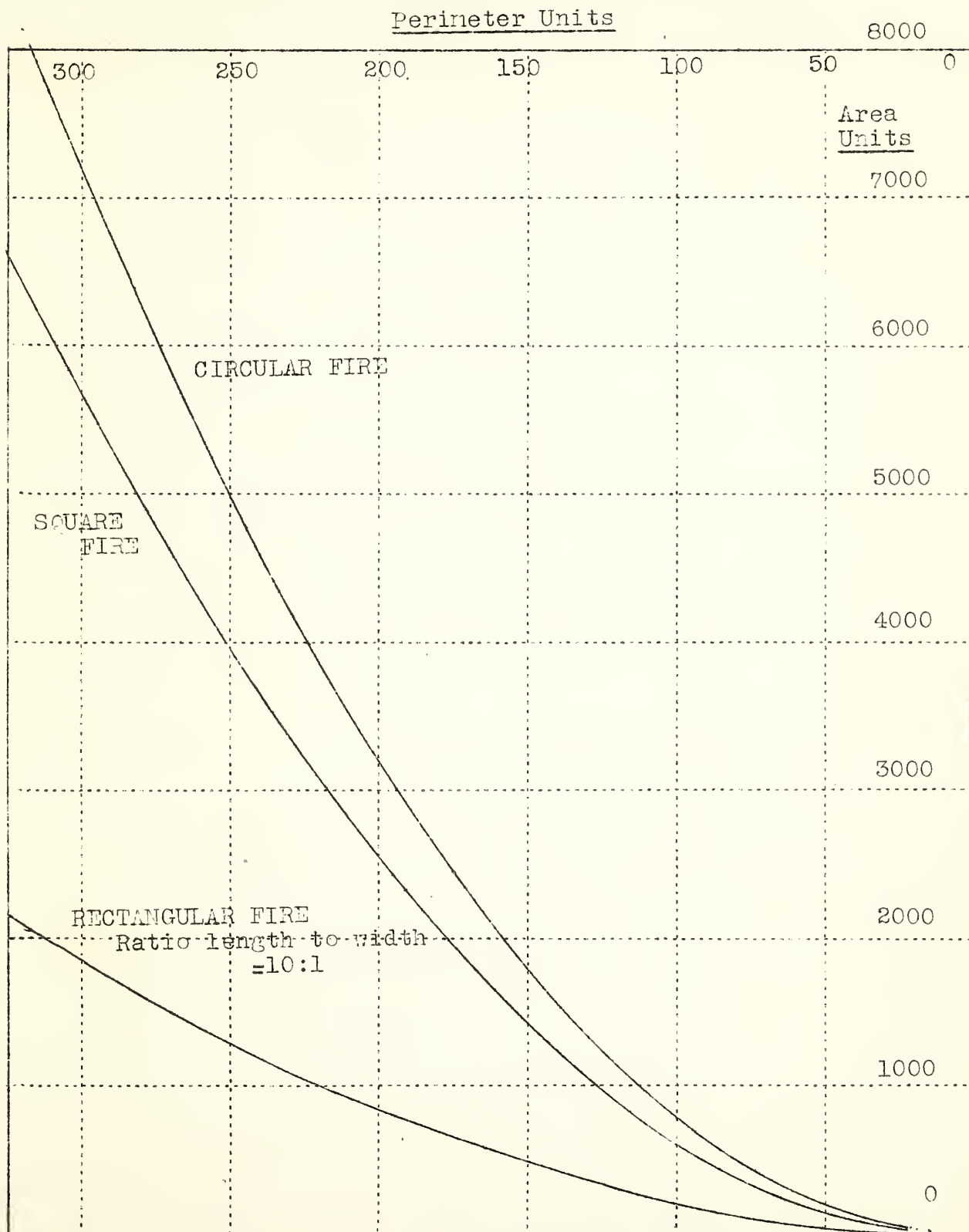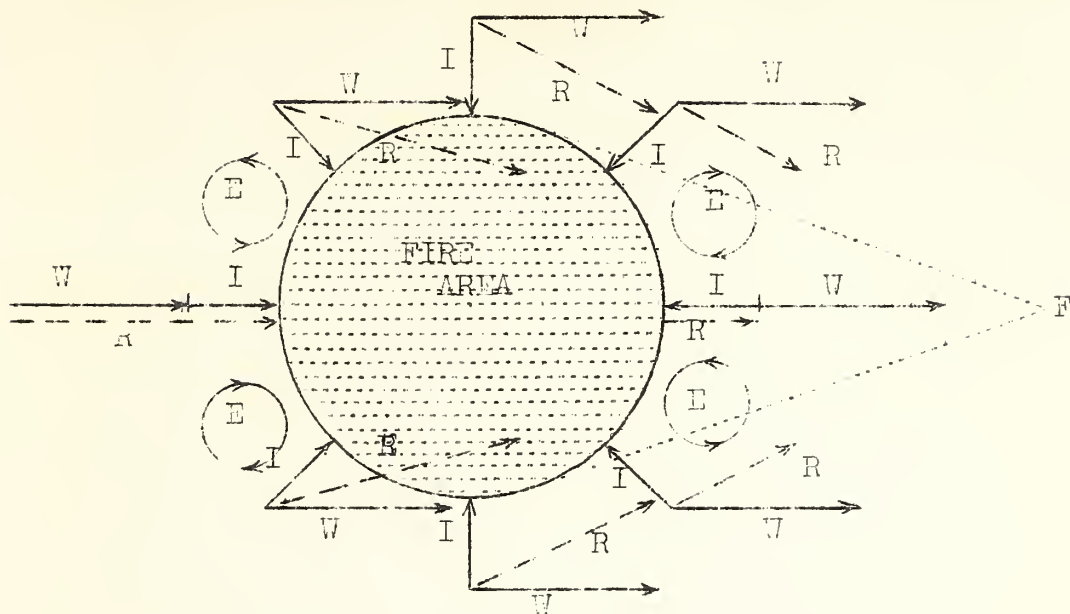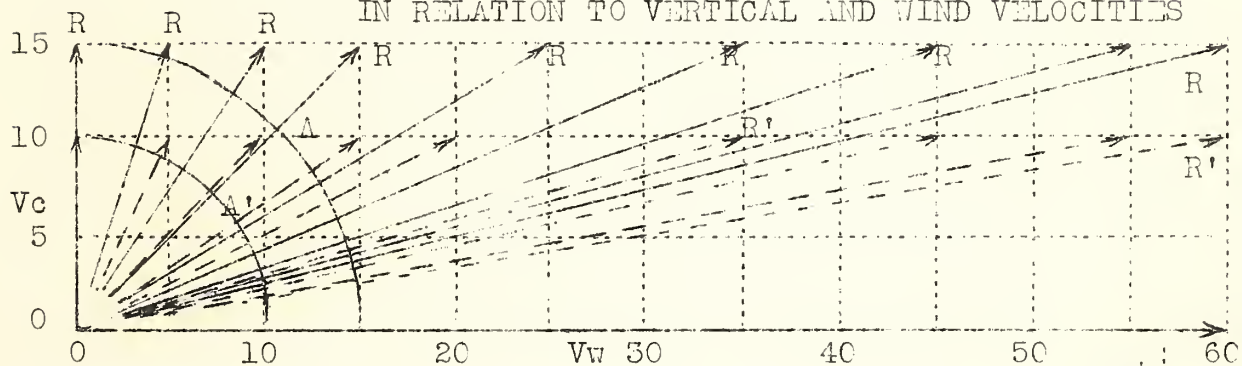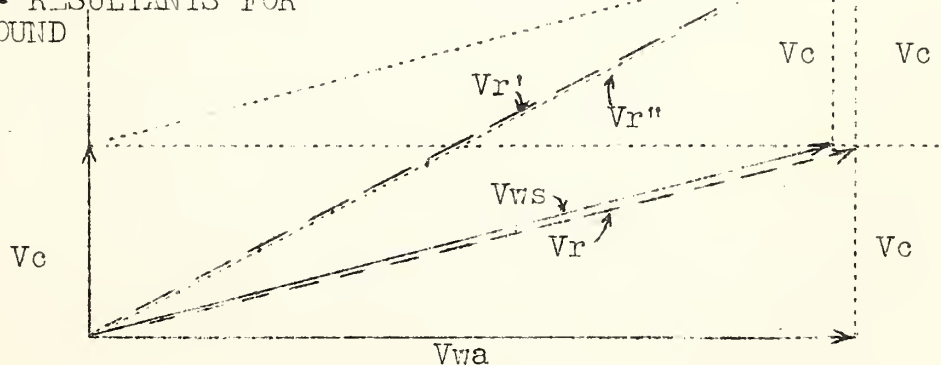
Vertical
Sections

Plan view

Fire

FIGURE 4 - FIRE WIND RESULTANTS AT SURFACE

FIGURE 5 - RESULTANT DRIFT OF SMOKE COLUMN
IN RELATION TO VERTICAL AND WIND VELOCITIES

FIGURE 5a - RESULTANTS FOR
SLOPING GROUND

In the figures, a is a dimension of the fire parallel to the prevailing wind direction, s is the slope angle between the "smoke" column and the horizontal, g is a similar slope angle between the horizontal and the ground, x is a cross sectional dimension of the "smoke" column, Vwp is the prevailing wind and Vwi the indraft velocities, Vr is a resultant velocity of the column, with components Vc (vertical column velocity) and Vw (prevailing wind velocity), all shown as vectors. The actual wind affecting a given part of a fire is a resultant of the general prevailing wind and an indraft component, as shown in Figure 4, the indraft being proportional to the density differences between the air at temperature Ta and the "smoke" column gases, at temperature Tc. The resultants shown in Figure 4 actually apply to points on the fire circumference (and not to points outside, as drawn for clearness). Obviously, the effect of air displacement by products of combustion is important only in a layer adjacent to the burning surface. The thickness of this layer is important in connection with air displacement, as will be shown later, but cannot be evaluated at present and hence will be given by the symbol y. The Vr of the column is a measure of the volume of gases leaving the burning surface in unit time, when considered in conjunction with the cross sectional area of the column, related in turn to the burning area by the slope angle. The volume obviously depends closely on the fire shape. In the following formula derivation, a simple square fire will be assumed, with side dimension a. Hence, the cross sectional area of the column becomes xa, a rectangular shape. For level ground, obviously,

$$x = a \sin s$$

For sloping ground, it can be shown that

$$x = a \sin (s - g)$$

The cross sectional column area for sloping ground is xa, or

$$Ac = a^2 \sin (s - g)$$

The volume of a unit layer of thickness y, for the fire area itself, is $a^2 y$. Obviously, the thickness of the layer when the cross section is not the fire but the column area, becomes

$$\frac{a^2 y}{a^2 \sin (s-g)}$$

The volume of the products of combustion evolved in unit time obviously is

$$Vpc = Ac\ Vr,\ \text{which is equal to}$$

$$a^2 \sin (s-g)Vr,\ \text{which is equal to}$$

$$a^2 \sin (s-g)\ \frac{Vwp}{\cos s}$$

for any ground slope, since the velocity of the wind (blowing parallel to the ground slope) is given by an anemometer exposed plumb in terms of a horizontal velocity and not a slope velocity. The number of <u>layers</u> of volume equal to the volume for the fire area and depth y, is given by

$$\frac{a^2 \sin (s-g)\ \dfrac{Vwp}{\cos s}}{\dfrac{a^2 y}{a^2 \sin (s-g)}}$$

which simplifies to

$$\frac{a^2 \sin^2(s-g)\ Vwp}{y \cos s}$$

representing the number of layers at temperature Tc.

At the same time, air is being fed into the fire by the prevailing wind (slope velocity, not horizontal projection) and by the indraft, as shown in the lower figure on page 31. For a simple fire, the indraft may be assumed to be equal on all sides (disregarding for the time being the effect of ground slope in accelerating or retarding air flow at the upper and lower parts of the fire, when on sloping ground, by increasing or decreasing the slope velocity component due to the effect of gravity, over and above the component due to density differences between the column and the air), and proportional to density differences. The volume of inflow due to the prevailing (slope) wind may be considered to be given by

$$Vwp\ (slope)y\ z$$

where z is a fire dimension given by the projection of the fire area on a straight line at right angles to the prevailing wind direction, the volume being appropriate to the temperature Ta. The number of layers of thickness y and fire area a^2 is given by

$$\frac{Vwp\ (slope)y\ z}{a^2y} \qquad \text{which reduces to}$$

$$\frac{Vwp\ (slope)}{a} \qquad \text{for a square fire, when the}$$

wind blows parallel to a side. This represents the number of layers fed in unit time by the prevailing wind only. The indraft similarly may be considered to feed air inward to the fire area along the entire fire circumference, the volume being given by

$$Vwi(y)\ 4a \qquad \text{for a square fire with side}$$

dimension a, and the number of layers of thickness y and equal to the fire area in cross section is given by

$$\frac{Vwi(y)4a}{a^2y} \qquad \text{which reduces to}$$

$$\frac{4Vwi}{a}$$

This number of layers due to indraft is additive to the number brought in by the prevailing wind, and hence the total number of layers of air fed into the fire by both indraft and prevailing wind becomes

$$\frac{Vwp(slope) + 4Vwi}{a}$$

Without considering the effect of slope on the indraft velocities of a simple, regular fire area (the effect is compensating), the true slope velocity of the prevailing wind, when the direction is directly up or down slope and not at some other angle, is given by

$$\frac{Vwp}{\cos g} \text{ (by anemometer)}$$

making the foregoing equation

$$\frac{Vwp\ (anem.) + 4Vwi\ \cos g}{a\ \cos g}$$

Parenthetically, it should be noted that if a fire on level ground is square, the shape of the column is rectangular under other than calm conditions, and if the fire is elliptical, the column may be circular, and vice versa.

The number of layers (or volume) of air is increased on mixing with the "smoke" column gases by the expansion due to change of temperature from Ta to Tc, so that the

foregoing equation becomes

27)
$$\frac{(460+Tc)\left[Vwp(anem.) + 4Vwi \cos g\right]}{(460+Ta)a \cos g}$$

thus making the air volume directly comparable with the volume of products of combustion, both at temperature Tc.

The proportion of air in the mixture of air and volatile wood or combustion products appears to be given, then, by the following equation, if combustion is incomplete or complete:

28)
$$\frac{\dfrac{(460+Tc)\left[Vwp + 4Vwi \cos g\right]}{(460+Ta)a \cos g}}{\dfrac{a^2 \sin^2(s-g)Vwp}{y \cos s}}$$

This merely indicates the proportion of air layers of given volume to similar layers of combustion products (including the air), considering that the air supply from outside sources near the ground is not mixed (outside the fire area itself) with smoke or products of combustion. The relation is a coefficient or multiplier of the oxygen supply formula 26, when the latter is altered to indicate the number of cubic feet of air supplied to the fire of given shape and under given conditions in unit time.

Equation 28 simplifies to

29)
$$\frac{(460+Tc)\left[Vwp + 4Vwi \cos g\right]y \cos s}{(460+Ta)\cos g\ a^3 \sin^2(s-g)Vwp}$$

It is apparent from the foregoing that the displacement or mixing of air will vary considerably with fire shape, fire orientation, wind velocity and thickness of the layer (y) in which active combustion occurs. Evaluation of y may be possible through other relations to be developed in later reports, or from field observations of flame heights. Evaluation will not be attempted in this report, and the relations given are merely suggestive of possible attacks on the problem of air displacement.

If Ac is cross sectional area of "smoke" column, Ab is the fire area, y is the depth of layer in which combustion is active, z is a dimension of the fire at right angles to the prevailing wind direction, Vwp is the true prevailing wind velocity (considering slope and orientation effects) and Cf the fire circumference,

a general form of equation 29, for any fire shape, orientation and ground slope, may be expressed as

30)
$$\frac{y \quad (zVwp + CfVwi)(460+Tc)}{AcVr \quad (460+Ta)}$$

Rate

Returning again to the question of oxygen supply, as already indicated Tc must be substituted for Ta in formula 26. In addition, for any given fire shape, area and other conditions, a certain volume of air is fed into the fire, this volume being given by

$$zyVwp + yCfVwi \quad \text{in general terms, and for}$$

the square fire assumed in prior derivations

$$ayVwp + \quad 4 \ ayVwi$$

In general terms, since formula 26 gives the weight of oxygen per cubic foot of air, the total weight in the given volume is

31)
$$\frac{(zyVwp + yCfVwi)(460+Tc) \quad .308(Ba-Bv)}{(460+Tc)(460+Ta)}$$

when volume is converted from volume at Ta to volume at Tc, and weight per cubic foot is given at Tc. This formula represents the total weight of oxygen supplied to any given fire under any conditions, but the effective weight of oxygen may be reduced by displacement of air by products of combustion, as given proportionally by the relation in formulae 29 or 30. Hence, for a general equation giving the total weight of available oxygen in unit time, formula 31 must be multiplied by formula 30, which gives

32) Total weight
oxygen
$$= \frac{.308(Ba-Bv)y^2(zVwp+CfVwi)^2(460+Tc)}{AcVr(460+Ta)^3}$$

The time unit is one second if velocities are given in feet per second, and the total weight of oxygen in any time becomes formula 32 multiplied by t, the time in seconds.

Formula 32, if applying to the square fire already assumed, becomes

33) Total wt.
oxygen
$$= \frac{.308(Ba-Bv)y^2(Vwp+4Vwi)^2 \ (460+Tc)\cos s}{(460+Ta)^2 \ a^2 \ \sin^2(s-g)Vwp}$$

Contact

For a given fuel, the amount of air required for complete combustion, or the effectiveness of a given air supply, depends on the perfection of the contact between air and fuel. In an absolute sense, evaluation of the degree of contact is extremely difficult, involving as it does the relative rates of air supply and evolution of combustion products, the position of the burning surface with relation to the air supply, the inter-diffusion of air and volatile combustibles during the exothermic stage of combustion, and contact with charcoal during the later stage of combustion (with the evolution of inflammable CO gas also important), the relative molecular velocities of the substances involved and the effects of contact or catalytic agents. No attempt will be made at present to evaluate absolute contact.

Relatively, it is apparent that the amount of air involved in combustion is proportional to the area of the burning surface. Air is in contact with fuel surfaces not burning but is of no consequence in the combustion process. Due to the fact that combustion cannot occur (theoretically) until all water is driven off from a limited fuel surface, the presence of water in fuels has no direct influence on contact as such, but influences combustion only as the water vapor driven off adds to the products of combustion and thus assists air displacement.

Under static conditions, the contact of air or oxygen with wood fuels may be considered to take place between and to involve very thin adjacent fuel and air layers. In connection with heat relationships to be developed in subsequent reports, the relation

$$\frac{1.47Ab}{Df}$$ seems quite important. Thus,

if the wood is pure wood substance (density 1.47), a certain amount of heat will be required to heat the fuel to the ignition point and to a given depth over a fixed unit surface area, and a certain volume of the fuel can be completely burned by a given quantity of air. If, however, the density of the fuel is less than 1.47 (see Table 3), the same quantity of air can combine completely with a larger volume of fuel, and less heat will be required to raise a given surface area to the ignition temperature, since there is less mass of actual wood substance involved for a layer of given depth. Subsequent reports will utilize this relation in detail; its mention here is merely suggestive.

If the air or oxygen supply is zero(entire "air" pressure due to water vapor, for example), obviously no amount of heat, however great, could be sufficient to cause active combustion other than that due to combination of a small part of the fuel constituents with the fuel oxygen, although decomposition and evolution of volatile elements of the fuel undoubtedly would occur. The inception hazard formula therefore must be so constructed as to indicate only the small hazard or combustibility due to fuel oxygen, when air supply is lacking. Under practical conditions, a zero air supply is not likely, although on the Matilija fire of 1932 in Southern California there were large unburned patches where the cover was thick and where the fire in general was most intense. Apparently, these patches were due to the evolution of combustion products at so rapid a rate that air was used up faster than it could be supplied (in view of the extent of the intense fire and the extremely blocked-in nature of the topography), and hence the fire died through lack of oxygen. Other causes may also have been operative, but the foregoing explanation seems soundest in view of the actual circumstances.

It is suggested that relative contact of oxygen or air may be expressed mathematically as follows:

If a unit weight of one pound of standard, dry wood fuel of cubical shape is taken as a reference unit, the volume in cubic feet is given by

33a) $V_f = \dfrac{1}{62.428\ D_f} = \dfrac{.01602}{D_f}$

where 62.428 is the weight of pure water per cubic foot at maximum density (4 deg. C, 39.2 F.). The length of a side of the cube is

33b) $\left[\dfrac{.01602}{D_f}\right]^{1/3}$ and the area of a side is

33c) $\left[\dfrac{.01602}{D_f}\right]^{2/3}$ and the total surface of the cube is

33d) $6\left[\dfrac{.01602}{D_f}\right]^{2/3}$ in square feet.

Relatively, the amount of oxygen in contact per square foot of fuel surface is given by the weight of oxygen per cubic foot of air, regardless of the thickness of the layer of air in contact with the fuel. Hence, the relative amount of oxygen in contact with the entire surface of the cube is given by

33c) $\qquad 6 \left[\dfrac{.01602}{Df}\right]^{2/3} \left[\dfrac{.308(Ba-Bv)}{460+Ti}\right]$

at the instant of ignition. Ignition being assumed to be instantaneous at the ignition point of 540 F., the rate of supply need not be considered, but merely static layers.

From formula 18, the weight of air required for complete combustion of one pound of standard dry wood fuel is 6.0099 lbs., when the air is dry. The volume of this air, regardless of its water vapor content, at the temperature of ignition, is given by equation 20, approximately, and amounts, very closely, to

33f) $\qquad \dfrac{4530}{(Ba-Bv)}$

when computed by constants carried out to a greater number of decimal places than are given in formula 20. Hence, in order for the pound of wood to be completely burned, that number of cubic feet of air must be in contact (relative) with the fuel surfaces. While a pound of fuel is not burned instantaneously at the ignition point, the relative values of all factors remain constant regardless of the actual unit quantity of fuel considered. Therefore, the relative completeness of combustion at the instant of ignition, using a pound of fuel as the unit, is given by

33g) $\qquad \dfrac{6 \left(\dfrac{.01602}{Df}\right)^{2/3} \left(\dfrac{.308(Ba-Bv)}{460+Ti}\right)}{\left(\dfrac{4530}{(Ba-Bv)}\right) \left(\dfrac{.308(Ba-Bv)}{460+Ti}\right)}$

which reduces to

33h) $\qquad \dfrac{.0000000390655\ (Ba-Bv)}{(Df)^{2/3}}$

eliminating oxygen as such from consideration.

This is merely a relative expression giving

$$\dfrac{\text{No. cu.ft. air in relative contact}}{\text{No. cu.ft. air required in relative contact for complete combustion}}$$

for a temperature of 540 F., the ignition point.

Application of this relation to the inception hazard formula will be made later.

The temperature of combustion

During combustion, various products are evolved and heated to a temperature depending on their specific heats, their masses and on the amount of heat evolved by the reaction minus conduction, radiation and convection losses. The products attain a given temperature representative of the convection losses, since they ascend at a more or less rapid rate as a convection or "smoke" column. Besides the factors mentioned, the temperature attained also depends on the speed of the reaction. The convection column cools by expansion and mixing with surrounding air while ascending, and also loses heat by radiation to space and back to the ground, as well as by conduction to the surrounding air. The temperature at the base of the column is closely representative, at least, of the amount of heat being generated by a fire, if the cover and other conditions are more or less uniform, thus making for uniformity in rate and amount of heat lost by the various processes. Under such circumstances, the temperature at the base of the column may be taken to be the fire temperature, with interesting and suggestive results. The actual temperature of the fire or convection column is very difficult to measure under field conditions by the various forms of pyrometers, which are expensive and require more or less skilled handling by persons familiar with the work. To make use of such instruments unnecessary, and yet secure practically accurate values for Tc (the temperature of the column base), it is suggested that use can be made of various simple relations and a formula derived from then, if measurements are made of

    1.) Ground slope, measured by clinometer.
    2.) Slope of the "smoke" column, measured in the same way.
    3.) The air temperature, measured by thermometer.
    4.) The wind velocity, measured by anemometer or balloon.

The theory is simple. The actual velocity of ascent of the column may be considered to be the resultant of a vertical component due to the difference in density between the column gases and the outside air, and the wind velocity (ordinarily in a direction parallel to the ground slope, in the lower layers). On level ground, in a calm (except for fire-produced indrafts, usually equal on all sides for a simple unit fire), the column ascends vertically, with an acceleration given by the equation

34) $a = \dfrac{g(T'-T)}{T}$ (Humphreys (11))

In moving air, however, the actual movement of the column may be considered as a resultant R as in Fig. 5 (page 31a), where Vc is the vertical column velocity component and Vw is the prevailing wind velocity, both in the same units. Data are given for various combinations of components, all graphed as vectors, and illustrating the construction of a simple diagram for computing resultants graphically.

On sloping ground, the same considerations apply, assuming that the wind blows parallel to the ground surface, as in Fig. 5a. Knowing the horizontal component of the prevailing wind velocity (the anemometer velocity corrected for instrumental error, since the anemometer, by its nature and plumb exposure, gives a horizontal component directly on sloping ground), the air temperature and the angle or slope between the column and ground, respectively, and the horizontal, the resultant velocity and the vertical component can be calculated, and then the temperature which, in combination with the air temperature, has been the fundamental cause of ascent.

In Humphreys equation for the acceleration a, g is the acceleration of gravity, T' is the absolute temperature of the column and T is the absolute temperature of the air, both measured at the same level. This formula, expressed in Fahrenheit degrees and feet becomes

35) $a = \dfrac{32.174(Tc-Ta)}{460+Ta}$

Velocity in general is equal to $\frac{1}{2}$ at, and for unit time t, to $\frac{1}{2}a$. Therefore,

36) $Vc = \dfrac{16.087(Tc-Ta)}{460+Ta}$

which is true only when the composition (and hence the density under standard conditions) of the air and of the gases in the column is identical. If the column gases differ in standard density compared with air, actual density values must be used in the foregoing equations, since temperature alone as used above merely assumes unit (or equal) densities for the two sets of gases.

Since density varies inversely as the absolute temperature (composition the same), the foregoing equations may be expressed by

37) $$V_c = \frac{16.087(D_a - D_c)}{D_c}$$

If s% represents the percent of grade or slope (defined as the vertical rise divided by the horizontal distance) of the "smoke" column above (plus) or below (minus) the horizontal, as shown in the figure below,

38) $$V_c = s\% V_w$$

or if the slope is expressed by an angle in degrees,

38a) $$V_c = \tan s \, V_w$$

Equating 37 and 38a, we have

39) $$\tan s \, V_w = \frac{16.087(D_a - D_c)}{D_c}$$

for any combinations of air and "smoke" column composition and for level ground only.

Also, for level ground and identical compositions for air and column, we have, from formula 36 and the foregoing:

40) $$T_c = \frac{\tan s \, V_w(460 + T_a)}{16.087} + T_a$$

and

41) $$V_c = s\% V_w \text{ or } \tan s \, V_w$$

and

42) $$V_r = \sqrt{V_c^2 + V_w^2}$$

or

43) $$V_r = V_w \sqrt{\tan^2 s + 1}$$
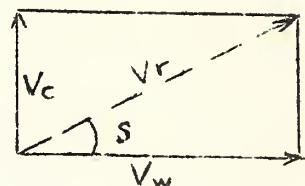
etc. For use in converting velocities in miles per hour to feet per second, the following should be used:

44) $$1.467 V_{mph} = V_{fps}$$

If g% represents the percent slope of the ground above or below the horizontal, it can be shown that

45) $$V_c = V_w(s\% - g\%)$$

and that

46) $Vr = Vw \sqrt{s\%^2 + 1}$

and that

47) $Tc = \dfrac{Vw(s\%-g\%)(460+Ta)}{16.087} + Ta$

for any ground slope, column composition same as air. If angles instead of grade percentage are used, formula 47 becomes

48) $Tc = \dfrac{Vw(\tan s - \tan g)(460+Ta)}{16.087} + Ta$

Using density (actual) instead of temperature, a general equation for any composition and temperature differences, for ground of any slope, may be secured.

The density of moist air, when referred to dry air at standard conditions as unity, is given by the expression

49) $Da = \dfrac{6.215(2.643Ba-Bv)}{459.6+Ta}$

From the percentage composition of the average dry wood, the weight of the products of combustion for incomplete and complete combustion of one pound of the dry wood may be computed from relations already given, resulting in values of approximately 6.991 lbs. for complete and 4.231 lbs. for incomplete combustion, calculated as follows:

Since the percentage by weight of oxygen in a given volume of dry air is 23.2, roughly, the percentage by weight of the remaining gases (termed nitrogen, although there are small quantities of other gases present), is 76.8%.

Combustible	% in 1 lb. fuel		Wt. Prods. per lb. combustible	Products, lbs.
Hydrogen.................6.06		x	8.94.........	.54176 H_2O
Carbon..................49.70		x	3.67........	1.82399 CO_2
Nitrogen in fuel.....1.05		x	0.0105.......	.01050 N_2
Nitrogen from air required for combustion; 76.8% x wt. air required or				
	76.8	x	6.0099.....	4.61560 N_2
Ash, incombustible, left behind, 1.89%				

Total wt. products, complete combustion....6.991 lbs.

The total for incomplete combustion is computed similarly, using a value of 2.33 for the weight of products per pound of combustible carbon, instead of 3.67 as for complete combustion (see Table 1), and changing the amount of air required in accordance with formula 19 on page 26.

The virtual densities of the gases in the column as a whole were computed as follows:

Product	% of total wt. of products		Standard* density		Relative Density Contribution
H2O......... 7.75		x	.804		.06231
CO2..........26.09		x	1.9769......		.51577
N2..........:.66.16		x	1.2568......		.83150

Virtual density of mixture of products......1.40958 for complete combustion, and the density relative to air, given by $\dfrac{1.40958}{1.2930}$ = 1.09016 or about 109% of dry air.

Note:* Density at 32 F., pressure 29.921", in grams per liter.

Similar computations gave a density value for the products of incomplete combustion relative to dry air of 92.45%. It should be noted that water in the fuel (fuel moisture content) when vaporized, adds to the products and decreases the virtual densities. This factor is not included in the foregoing computations.

Thus, the density of the column, with complete combustion and dry fuel, is given by

50)   Dc = 1.09016 x air at same temperature and pressure, and

51)   Dc = .9245 x air at same temperature and pressure,

for incomplete combustion.

A formula (49) for the density of air containing any percentage of moisture has already been secured, and substituting density values computed by this formula (modified by values from 50 and 51, above)in formula 39 (with tan s-tang x Vw substituted for the left side to take care of ground of any slope), using appropriate temperatures for the column and the air, the formulae for Tc become

52) Tc = .067767Vw(tan s - tan g)(460+Ta)+1.09Ta+41.4

for any conditions of composition, slope, temperature,
relative humidity and wind velocity for complete com-
bustion of standard dry wood fuel of composition given
in Table 2, *except slopes of 90° and zero wind velocities.*

53) Tc = .062162Vw(tan s - tan g)(460+Ta)+Ta

for similar conditions, except that column composition
is same as that of the surrounding air, and combustion
is not necessarily involved.

54) Tc = .057468Vw(tan s - Tan g)(460+Ta)+.9245Ta-34.7

for conditions as in first formula, but for incomplete
combustion of standard dry wood fuel.

The implications of this formula of general type
for calculating Tc are rather far reaching. For ex-
ample, depending on the temperature of the column and
of the air, if the fuel is of certain type, the
rate of supply of oxygen (and speed of the reaction,
other things the same), and the heats lost by convec-
tion, conduction and radiation are known, then the
heat produced by the fire compared with what should be
produced by complete combustion under the given
conditions appears to indicate the degree of complete-
ness of combustion. Changes in values of constants in
the Tc formulae occur with changes in the completeness
of combustion. At present, the range in values of
these formula constants under various conditions varies
with a density range of about $16\frac{1}{2}\%$. By using the
equation for air and column of same densities (53),
where doubt exists as to the completeness of combustion,
the possible error can be cut to that appropriate to
a density range of but 9%.

With practically accurate values for Tc from the
foregoing formulae, it is relatively easy to compute,
for example, the indraft velocities that will be pro-
duced under various conditions. Although the barome-
tric pressure and the vapor pressure are factors in the
density of moist air, they drop out in simplification
of the Tc equations, since both the air and the column
are under the air pressure, and the vapor in the air,
as the air joins the products of combustion, is the same
amount affecting the products of combustion and their
virtual density, and hence these factors cancel out.

Besides the problem of determining the complete-
ness of the combustion process in order to use proper
constants in the Tc formulae in individual cases, pos-
sible sources of error lie in the following:

1.) Use of surface wind velocity, when in fact the velocity usually increases with altitude.
2.) Use of surface temperatures, when in fact the velocity of ascent, once the column gases have left the surface, becomes affected by the temperature lapse rate of the air.
3.) Use of virtual relative densities at the surface, when in fact changes due to temperature, pressure and mixing occur with altitude.

These errors affect the trend or slope s of the column, primarily. These and other less important sources of error can be kept within reasonable bounds by the following precautions:

1.) Use of ceiling or pilot balloons to secure the wind velocity, a vertical angle being taken after one, two or three minutes of flight only, the velocity secured being representative of the average velocity at low elevations (where the angle s is measured), and to a limited extent allowing also for lapse rate variations.

2.) Not using formulae for narrow, boxed-in canyons where wind eddies and fluctuations are extremely pronounced, or when air is very turbulent for other reasons.

3.) Measuring angles only for the lower part of the column, and averaging the minor variations of the column from a straight line.

Most investigators are agreed that definite values for "volume" of heat generated by forest fires under different conditions would be of considerable value, and the formulae given in this report offer a suggestive means for economical and widespread observation of this factor, although the formulae cannot be said to be yet in final form.

GENERAL FIRE HAZARD RATING FORMULAE

Although the foregoing does not attempt to give final and complete fire hazard formulae, it is believed to be desirable to indicate how various equations for separate factors may be combined for final ratings. Obviously, the fundamental principle is to combine all factors affecting fire hazard directly, and to divide by all combined factors affecting fire hazard inversely.

It cannot be too strongly emphasized that this preliminary study necessarily goes into considerable detail, but the use of formulae by field personnel is not contemplated. In combining separate equations into a final formula, large sections of the detailed

relations cancel out, and further simplification can be effected by eliminating those factors which prove to be of minor importance. In arriving at final ratings, however, it is desirable to formulate detailed equations on the same principle as that involved in simple arithmetic, where intermediate calculations must be carried to more places than in the answer in order to insure accuracy of the decimal places given in the result. Further, it is likely that final formulae can be expressed adequately by a few pre-computed graphs and tables, making calculation unnecessary, other than minor arithmetical operations.

Inception hazard, in general, may be considered to be adequately expressed for practical fire hazard rating purposes, if the following are known:

1. The heat required to cause ignition.
2. The available relative air supply.
3. The effective heating value of ignition agents.

Expressing the effective heat output of any given igniting agent by the symbol HVi, without attempt at numerical evaluation, a general formula for inception hazard appears to be the following:

55) $HI = \dfrac{1.47 \; HVi \; \times \; air \; supply}{Df \; HIG}$

if a unit weight (one pound) of fuel is taken as standard, it is assumed that the heats are applied to unit fuel surface areas (introducing the effects of fuel density, as discussed on page 37), and if pure wood substance (density 1.47) is taken as a reference point for other types of cover. The relative air supply is given by formula 33h. To this must be added the fuel oxygen, since if the air supply were zero, partial combustion still could take place, as already discussed. At the instant of ignition, combustion has just started, and air displacement by products of combustion does not enter the picture. Numerically, the HI formula may now be expressed as follows:

56) $HI = 1.47 \; HVi \; \dfrac{.000000030146 \left[(Ba-Bv) + 7574351 \; Df^{2/3} \right]}{Df^{2/3}}$

HIG as in Formula 2, except last element $SHa(Ti-Ta)Wa$ becomes

$SHa(540-Ta)6.0099$ x formula 33h, thus giving relatively the amount of air that must be heated to the ignition point for any given degree of completeness of combustion.

Expressed completely, and simplified, this formula becomes

57) $HI = HVi \ .000000044315 \left[\dfrac{(Ba-Bv) + 7574351 \ Df^{2/3}}{Df^{2/3}} \right]$

$$\overline{Df \left[SHf(540-Tf)+35+FM\% \left[.5(32-Ts)+144 \ldots \right. \right.}$$

(cont.)..+(Tb-Tw)+Hv+SHv(540-Tb)].....

(Cont.)...+SHa(540-Ta)$\dfrac{.00000023478(Ba-Bv)}{Df^{2/3}} \bigg]$

The value of the coefficient for the last expression (indicating the amount of heat required to raise air to the ignition point) is merely formula 33h multiplied by 6.0099, the weight of air involved in complete combustion of one pound of fuel. Formula 33h, since it represents the relative completeness of combustion (exclusive of the fuel oxygen), obviously determines the amount of air that must be heated for any given degree of completeness of combustion when thus used as a multiplier of the amount of air required for complete combustion (unity).

The value of formula 33h for use in the numerator as a factor showing relative air supply, obviously must be altered to include the <u>fuel</u> oxygen <u>in similar units</u> so that zero hazard does not occur when air supply is zero. Instead, if the fuel oxygen is added to both the numerator and denominator of formula 33g, under the foregoing conditions a ~~small~~ hazard will be indicated due to partial combustion by reason of fuel oxygen. The steps in deriving the proper numerator coefficient are as follows:
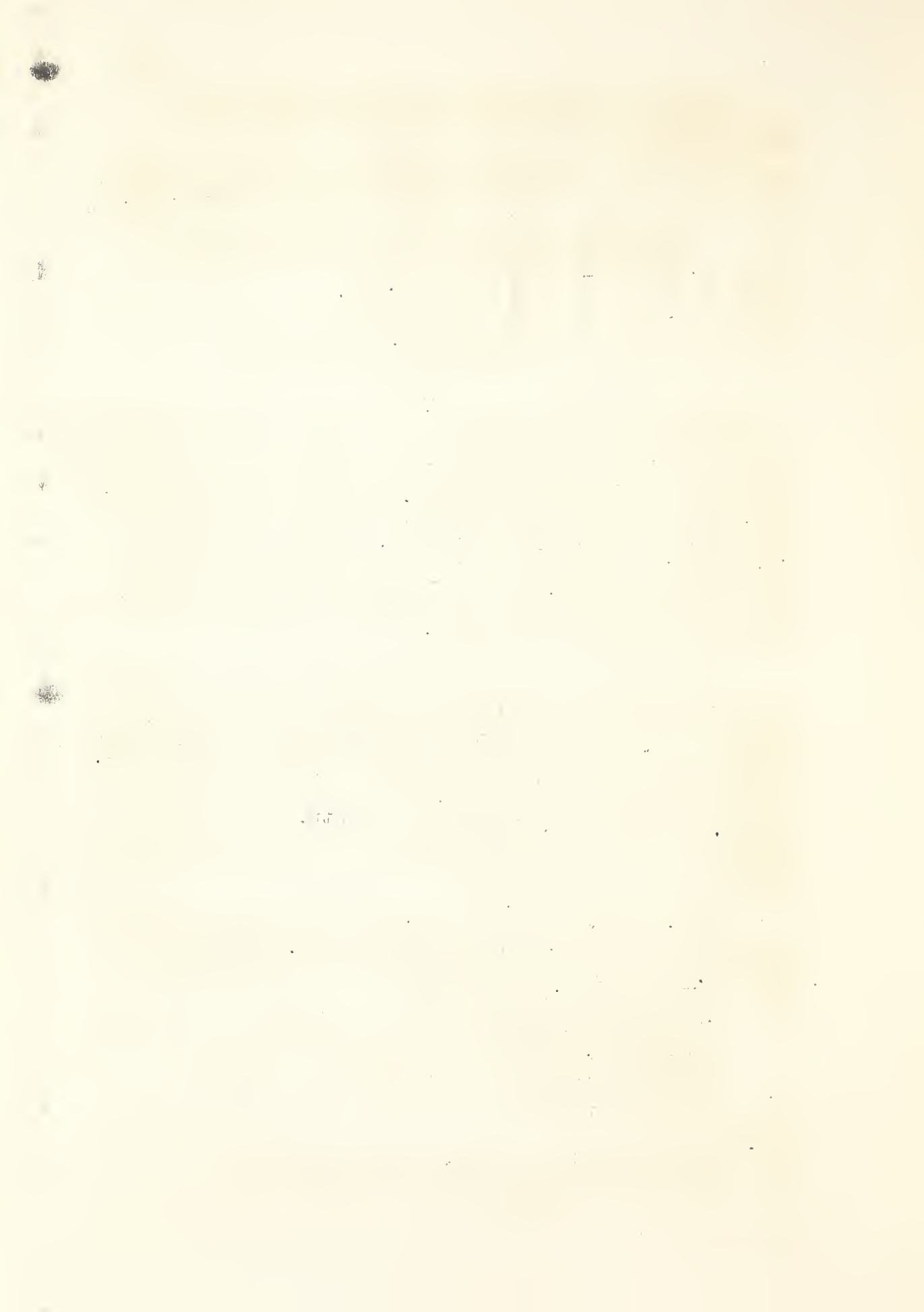
In standard wood fuel, 41.3 % is oxygen, or there is .413 lb. of oxygen per pound of fuel. Hence, the relative degree of completeness of combustion is

58) $\dfrac{6(.01602)^{2/3} \ .308(Ba-Bv)}{Df^{2/3}(460+Ti)} \ + \ .413$

$\dfrac{4530(Ba-Bv).308}{(Ba-Bv)(460+Ti)} \ + \ .413$

which simplifies to

59) $\dfrac{.000000030146 \left[(Ba-Bv) + 7574351 \ Df^{2/3} \right]}{Df^{2/3}}$

In formula 57, a value of 540 F. is substituted
for the ignition temperature, the specific heat of
water is taken as one, a unit weight of fuel is em-
ployed, the heat of wetting adopted is the approximate
value of 35 Btu per pound for coniferous species found
by Dunlap, the heat of fusion is given as 144 Btu, and
the relative completeness of combustion as determined
by relative air supply is given by suitable coeffi-
cients or multipliers. Values for the various tem-
peratures, specific heats and the heat of vaporization
indicated by symbols in the formula, will be found in
Tables 3, 6 and 7, and in Figure 2.

To illustrate the method of calculation, the
following conditions will be assumed:

Ba:29.921" Bv:0" Df: .490 Tf, Ta, Ts:30 FM%:10

With a fuel temperature of 30, the range through which
the fuel must be raised is 540-30 or 510 deg. F., and
the mean temperature is $\frac{540+30}{2}$ or 285 F. The mean

specific heat of dry wood at this mean temperature,
from Figure 2, is about .41, and the total heat required
for the wood is .41 x 510 or 209 Btu. The heat required
to overcome the chemical attraction between the wood and
its contained moisture is 35 Btu. The fuel moisture is
in the form of ice, and hence all stages in the con-
version of the fuel moisture to vapor at the ignition
temperature must be considered. The specific heat of
ice is .5, the temperature range is 32-30 or 2 degrees
and the heat required is .5 x 2 = 1 Btu, for one pound
of fuel moisture. To this must be added the heat of
fusion (melting), amounting to 144 Btu. The boiling
point temperature of water at a barometric pressure of
29.921" is 212 F. (from Table 6), and as the tempera-
ture of the water (melted ice) is 32 F., the temperature
range between the boiling and melting points of water
is 212-32 or 180 degrees, and since the mean specific
heat of water is approximately 1, the heat required is
1 x 180 or 180 Btu per pound of water. From Table 6,
the heat of vaporization at a barometric pressure of
29.921" is 971 Btu. From Figure 2, for a mean tempera-
ture of $\frac{540+212}{2}$ or 376 F., the mean specific heat of

water vapor is about .488, the temperature range is
540-212 or 328 degrees, and the heat involved is
.488 x 328 = 160 Btu. All of the foregoing values re-
lating to the fuel moisture must be added together and
the sum be multiplied by the fuel moisture percentage
(since the latter represents the actual weight of water
concerned, rather than the unit pound used in the cal-
culations so far), and hence the heat required for elimi-
nation of fuel moisture is

$$(1 + 144 + 180 + 971 + 160) \ .10 = 145.6 \text{ Btu}$$

From Figure 2, the mean specific heat of dry air for a mean temperature of $(540+30)\frac{1}{2}$ or 285 F. is about .24, and as the temperature range is 510, the heat required to raise one pound of air to the ignition point is .24 x 510 or 122 Btu. However, if combustion completeness is adequately represented by the coefficient already formulated, the actual amount of heat required for the actual amount of air present is

$$122 \ (\frac{.00000023478(Ba-Bv)}{Df^{2/3}}$$

which gives a value of .0000000003 Btu, thus indicating that the air factor in relation to the heat required for ignition need not be considered, and that the coefficient in the denominator of formula 57 and the expression SHa(540-Ta) should be dropped. Otherwise, the numerical values computed may be totalled as follows:

HIG = 209+35+146 = 390 Btu.

Inserting this value in formula 57 (see also formula 55), and carrying out the indicated computations, a value for inception hazard is secured:

HI = HVi .0017565

Similarly, using assumed conditions identical with the foregoing, but with Ta, Tf and Tw 100 F. instead of 30 F., the inception hazard is found to be

HI = HVi .0019798

If HVi is not considered, or, rather, the HVi is the same in both cases, the relative hazard under the second condition of temperature 100 F., compared with that under the first condition of temperature 30F., is

$$\frac{.0019798}{.0017565} = 1.127 \text{ plus, or, in other words,}$$

due solely to a rise in temperature of 70 deg. F. from 30 to 100, the relative hazard increased by 12.7%.

If we assume a temperature of 100, and alter the vapor pressure (Bv) to a value corresponding to 100% relative humidity (Bv: 1.916"), the relative hazard becomes

HI = HVi .0019795, about, indicating that

relative humidity as such (compare rating of .0019795 with that of .0019798) is of no practical importance in affecting fire inception hazard directly, <u>except as it results in fuel moisture changes</u>. In the given example, the fuel moisture was assumed to remain at 10% in spite of a rise in humidity from zero to 100%. Actually, if the rise in humidity was slow, the fuel moisture would eventually reach an equilibrium value of about 34% (see Figure 1).

These computations also show that, <u>so far as fire INCEPTION is concerned</u>, the variations in air oxygen supply with relative humidity, pressure and altitude, at the ignition temperature of 540 F., are of little consequence. This does not hold for fire TRANSLATION hazard, however, since the temperature generated by the fire may be widely variable under different conditions, the rate of supply is also variable as affected primarily by wind movement, and altitude (or decreased pressure) and displacement by products of combustion produce marked effects. These all lead to considerable fluctuations in the amount of oxygen available for combustion under different conditions. It appears that it is the <u>fuel</u> oxygen that is of primary importance in <u>inception</u> hazard, especially under ordinary circumstances when a normal air supply is present at the instant of ignition.

Formula 57 therefore may be simplified by elimination of the inconsequential elements, and becomes:

60) $HI = \dfrac{HVi \ .33566}{Df\ [SHf(540-Tf)+35\ +\ FM\%[.5(32-Ts)+144...}$
(cont.)..$+(Tb-Tw)+Hv+SHv(540-Tb)]]$

giving practically identical results.

This formula is representative of "instantaneous" inception hazard, as distinct from "areal" or "geographical hazard", since time as such is not directly involved (consideration deferred until HVi is evaluated) and comparisons are between <u>unit weights</u> of fuel, and not between the varying quantities of fuel to be found naturally on different unit ground areas. The formula represents theoretical relative hazard of fire inception for

1.) A unit weight (1 lb.) of standard wood fuel with composition as given in Table 2.
2.) A solid fuel in the form of a cube, having a surface area exposed to air and igniting agents appropriate to this shape.

3.) Any species of wood or other solid forest
fuel for which good oven dry densities are available.

4.) Any type of cover (if suitable changes in
constants are made to allow for variations in fuel
shape, surface area, oxygen content and ignition tem-
perature), referred to pure wood substance (density
1.47) as a standard or reference point.

5.) Ignition temperature of 540 F., assumed as
fixed and invariable so that it may be used as an
index or reference point (fuels of different ignition
temperature are not represented by the formula as
given, but the formula structure will be identical).

6.) Any air, fuel and fuel moisture temperatures.

7.) Any fuel moisture content.

8.) Any altitude or atmospheric pressure.

9.) Any state of fuel moisture.

10.) Any igniting agent emitting heat considered
uniformly distributed over the entire exposed fuel
surface, the fuel being of unit weight.

11.) Any degree of insolation (through effects on
fuel, fuel moisture and air temperatures).

Expressed more generally, the formula becomes

61) $HI = \dfrac{1.47 \ HVi \ K}{Df \ HIG}$

where K, a constant for any given fuel (nature, shape,
exposed surface area, etc.) of unit weight is given by

62) $K = \dfrac{\dfrac{Aes \ Wo + Wfo}{Wacc \ Wo + Wfo}}{Ba-Bv}$ (see page 21a for symbols)

Formulae 60 and 61 compare unit weights of fuel,
assumed to be concentrated into a solid block. In nature,
however, fuel is distributed over the ground area in
numerous individual pieces, hence, for actual geographical
or areal (map) ratings, the actual quantity of fuel per
unit ground area (horizontal projection) must be used
as a multiplier of the formulae in order to compare
different unit areas or regions. Satisfactory units
for areal ratings would be tons of fuel per square mile,
for quantity and area. Over an area, instead of con-
centrated blocks of fuel of uniform shape, there are
very numerous individual pieces of different shapes and
sizes, such as twigs, logs, branches, foliage, duff
layers and grasses. Thus, if a compact duff layer is
to be considered, its exposed surface is practically the
area of the actual ground surface (not a horizontal pro-
jection, but taking in all irregularities) per square
mile (horizontal projection). If the horizontally pro-

jected square mile is used, there would be more actual
fuel present per square mile, for a given stand density,
on sloping than on level ground, due to greater slope
distance. A square mile seems to be a satisfactory
unit, but may be translated into other areal units if
required. A square foot is not satisfactory since ade-
quate account of the many types and physical forms of
forest fuels cannot be taken by so small a sample plot.

It is possible that data collected in connection
with the California cover type map can be utilized to
secure estimates of quantity of fuel in an areal sense.
In estimating the quantity, it will be necessary to
employ average density values for the different types
of fuels, and in some cases, density values may have
to be found from additional laboratory tests by forest
agencies (as for some of the brush fuels, grasses, barks
and foliage). By approximations, estimates or limited
sample plot measurements and observations, it should be
possible to approximate the exposed total fuel quantity
and surface area for various districts and broad cover
type zones. The quantity of fuel obviously affects the
chances for ignition in that, other things the same,
the probability for ignition varies directly with fuel
quantity, no ignition being possible in the absence of
fuel. Also, the larger the exposed surface, the better
are the chances for ignition. It is apparent that the
quantity and surface work in a relative sense, and that
while both are directly related to the chances for
ignition, in reality they operate as a ratio, which
combines the effects of quantity and surface, and tenta-
tively, at least, the foregoing formulae may be multi-
plied by a coefficient given by

$$\frac{\text{es (total)}}{\text{Wf (total)}}$$

This means that given a heavy fuel of given exposed sur-
face (such as a log), the ignition hazard is much less
than the same weight of fuel, but with a much greater
surface. This simple ratio is not all that is involved,
of course, but at present will be considered as fully
meeting practical requirements.

Given the total exposed surface per square mile,
the total quantity of fuel in the same area and the
heating value per unit weight of fuel, some idea of the
"conflagration" hazard may be gained, in conjunction with
other formula factors. In other words, a relative mea-
sure of the total number of heat units that possibly
could be liberated by complete combustion would be gained,

and in connection with weather and miscellaneous
factors inserted in a translation hazard formula,
the approximate rate of combustion could be found,
and hence the relative difficulty of control. It
must be borne in mind that precision in formula
factor measurements or estimates is neither nec-
essary nor possible, and in any case are not desir-
able for practical rating work, as precision usually
requires too intricate formulae. Periodical exami-
nation of a few sample plots should take care of
the seasonal and periodic changes in quantity and
surface of fuels for current hazard rating purposes
(rather than broad general averages for a period of
years).

Finally, a general fire inception formula,
showing theoretical relative hazard, including the
factors just discussed and for any time (instan-
taneous, not a period, necessarily) and any area, may
be expressed by

63) $HI = \dfrac{1.47 \ HVi \ K \ Aes(total)}{Df \ HIG \ Wf(total)}$

Also, formula 60 may be expressed for a compact
duff layer instead of a cube as follows (assuming that
the top <u>inch</u> of duff is that primarily involved in
fire inception in this type of cover, and that the duff
composition is the same as that for standard wood fuel
as given in Table 2):

64) $HI = \dfrac{HVi \ .33582}{Df \ HIG}$

the changed coefficient .33582 being found from the
relation given in formula 58, thus:

$$\dfrac{\dfrac{.01602}{.08333Df} \ \dfrac{.308(Ba-Bv)}{1000} + .413}{\dfrac{4530}{Ba-Bv} \ \dfrac{.308(Ba-Bv)}{1000} + .413} = \dfrac{.4131-}{1.80824} = .22845(x \ 1.47)..$$

$$..= .33582$$

where $\dfrac{.01602}{Df}$ = (relative volume of duff weighing 1 lb.)

$.08333$ = (depth of duff layer in feet)

This ratio is equivalent to the first part of the equa-
tion just given for computing the coefficient, and is
equal to the <u>surface area</u> in square feet of the duff layer.
The remainder of the equation represents the relations
already discussed, and the result is based on the elim-
inations of unimportant factors already mentioned.

It is clear that simple tables and/or graphs can be prepared to make the computations very easy. It is planned to compute tables for a few cover types and fuel conditions for use in checking ratings during the summer work of the mobile fire weather forecasting unit.

SUMMARY

Definite, approximate relative fire inception hazard rating formulae of theoretical nature have been developed in this report on physical, chemical, and mathematical grounds, employing what appear to be reasonable and logical assumptions where needed for calculation purposes. Some equations for eventual rating of translation hazard have also been developed, but a complete translation hazard formula has not been attempted. The inception hazard formula makes no present attempt at numerical evaluation of the effective heating power of various igniting agents. Granting that the assumptions are sound and the mechanics of calculation correct, whether or not the formulae are strictly correct or sufficiently so for practical purposes depends on the results of detailed and systematic checking against accurate fire, weather and miscellaneous data. Some changes in formula constants or arrangements may be found to be necessary. It is believed, however, that the general results of this study are suggestive of a definite method of attack on the fire hazard rating problem which deals with more or less fundamental aspects of the combustion process as concerned in forest fires, rather than with single isolated factors, important in themselves but not adequate to express fully the ultimate hazard. As further study is completed, additional progress reports will be submitted. A definite program of fire hazard rating study has not been set up; prosecution of such study is incidental to fire weather study in general.

This report gives the results of intermittent field and office work during the past seven years, in connection with general fire weather study carried on as a part of the work of the fire weather service of the U. S. Weather Bureau in fire weather district No. 1 (California and Southwestern Nevada). The report forms a part of the Weather Bureau contribution to the work of the California Region going fire study committee, having as members the Regional Forester, the Director of the California Forest Experiment Station, assigned Experiment Station personnel, the Assistant Regional Forester in charge of Fire Control and the Fire Weather Official of the Weather Bureau.

Strictly, the report is not a duplication of any other study, so far as known, since it employs a divergent (theoretical) method, based primarily on meteorological considerations. The general problem of fire hazard rating, however, is being attacked by forest protection agencies, and pertains primarily to their field of investigation. In general, the methods being followed by these agencies are the experimental and empirical types mentioned earlier in this report. An independent theoretical study thus serves as a desirable and useful mutual check, and may possibly be instrumental in presenting new material.

Additional study required

Besides the checking of the relationships given, by comparison with actual fire behavior, it will be necessary for really satisfactory ratings to secure by laboratory tests values for the oven dry densities, chemical compositions and heating values of all of the major types of forest fuels (including woods, barks, foliage, duff and grasses), as well as approximate evaluations of quantity and exposed surface of fuels by surveys of sample plots or otherwise (as from cover type map data), the supplying of these required data being   the province of the forest protection agencies. In addition, evaluation of the effective heating value of igniting agents in terms of British thermal units must be attempted, and formulae of general type must be produced for fire translation or spread as well as inception. When and if both inception and translation formulae are available and check with reality, the two probably must be combined in some way, to give a measure of general fire hazard.

It is recommended that formula 64, or this formula with modified coefficients depending on the type and nature of fuel considered, be used in connection with checking against fire data, or for tentative rating of inception hazard, exclusive of the factor of effective heat output of various igniting agents. Until this factor is evaluated, checking may not be said to be complete or adequate.